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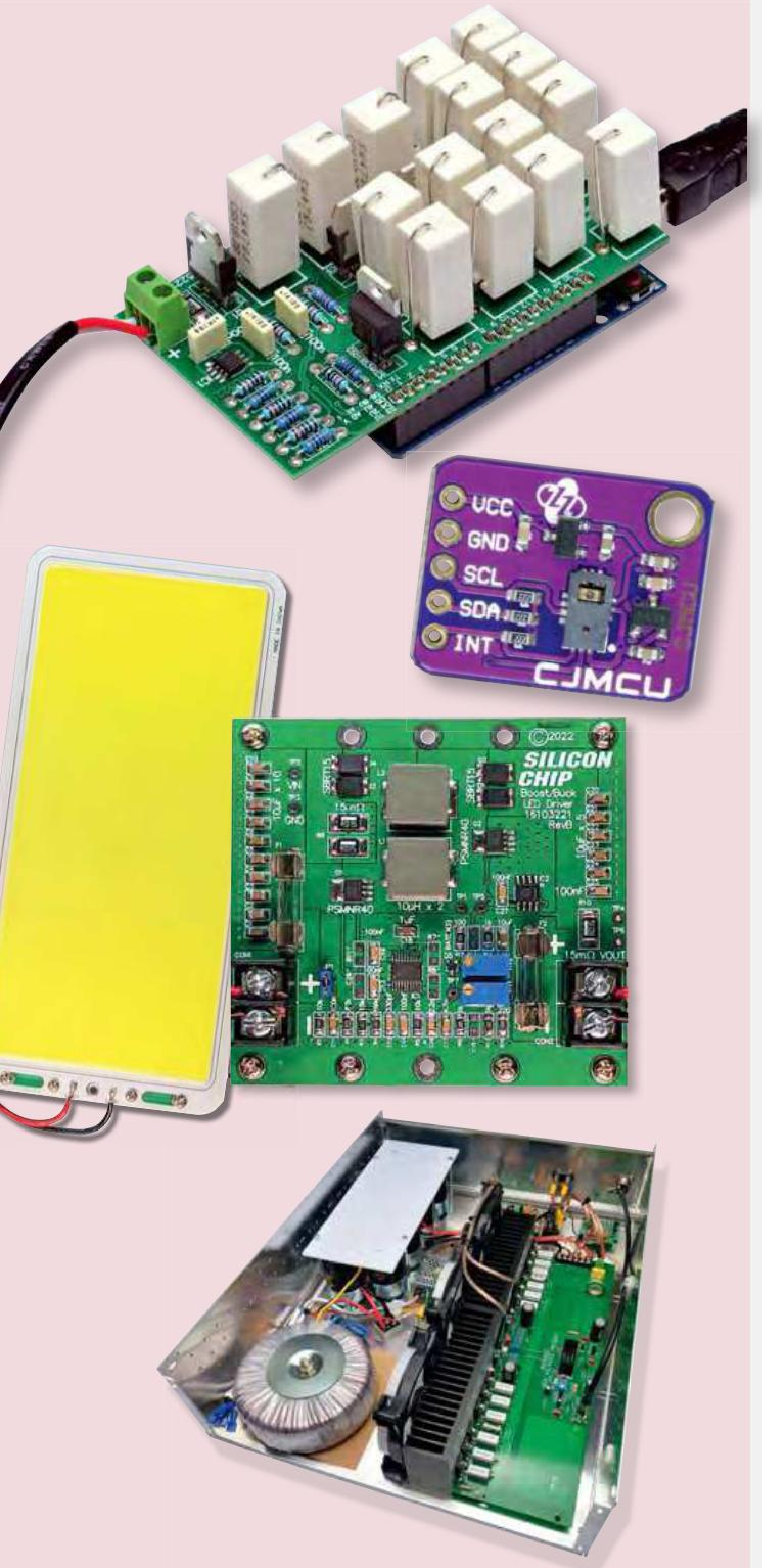

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The July 2023 issue of *Practical Electronics* will be published on Thursday, 1 June 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by **LOUIS MEULSTEE**

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The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

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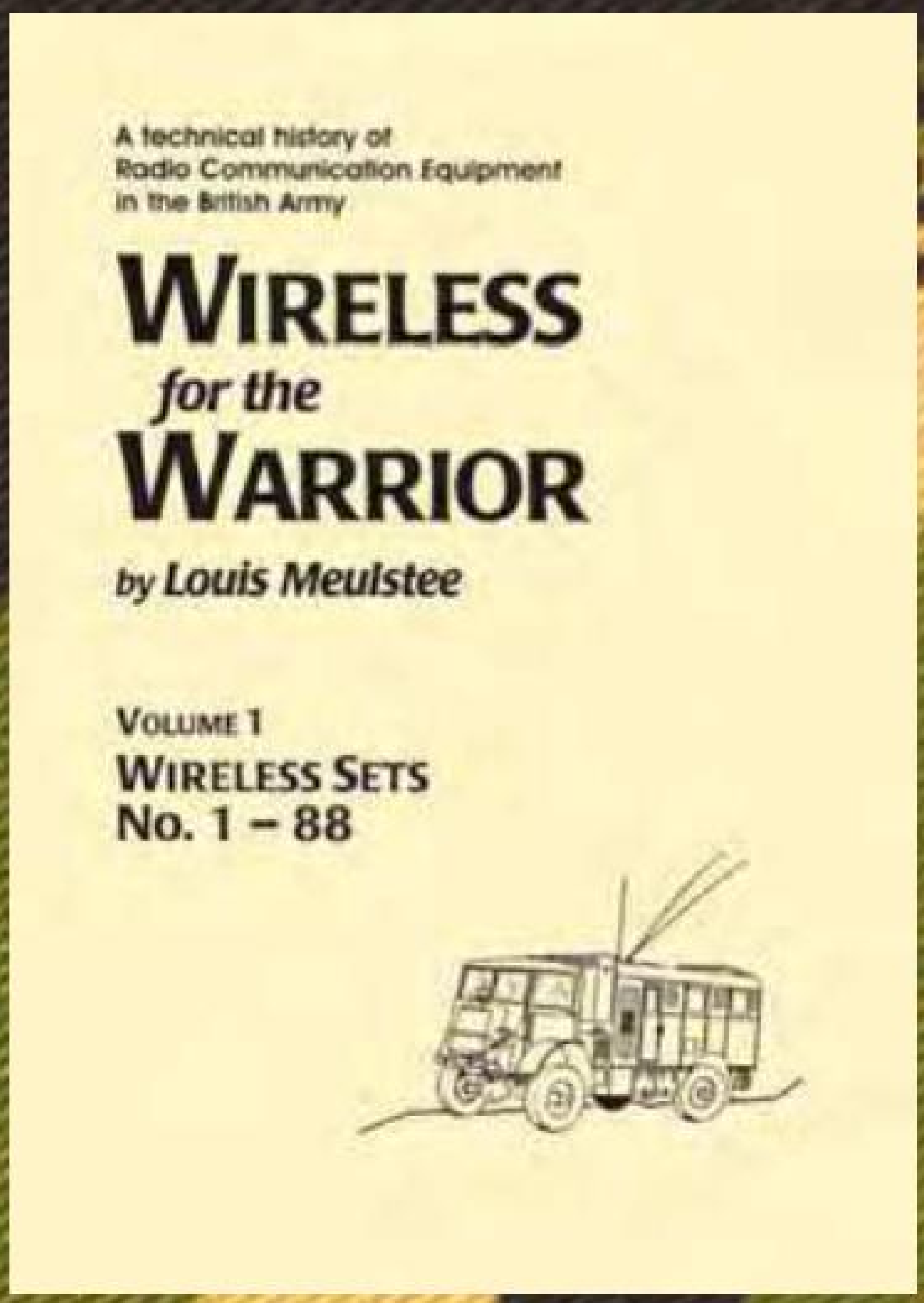

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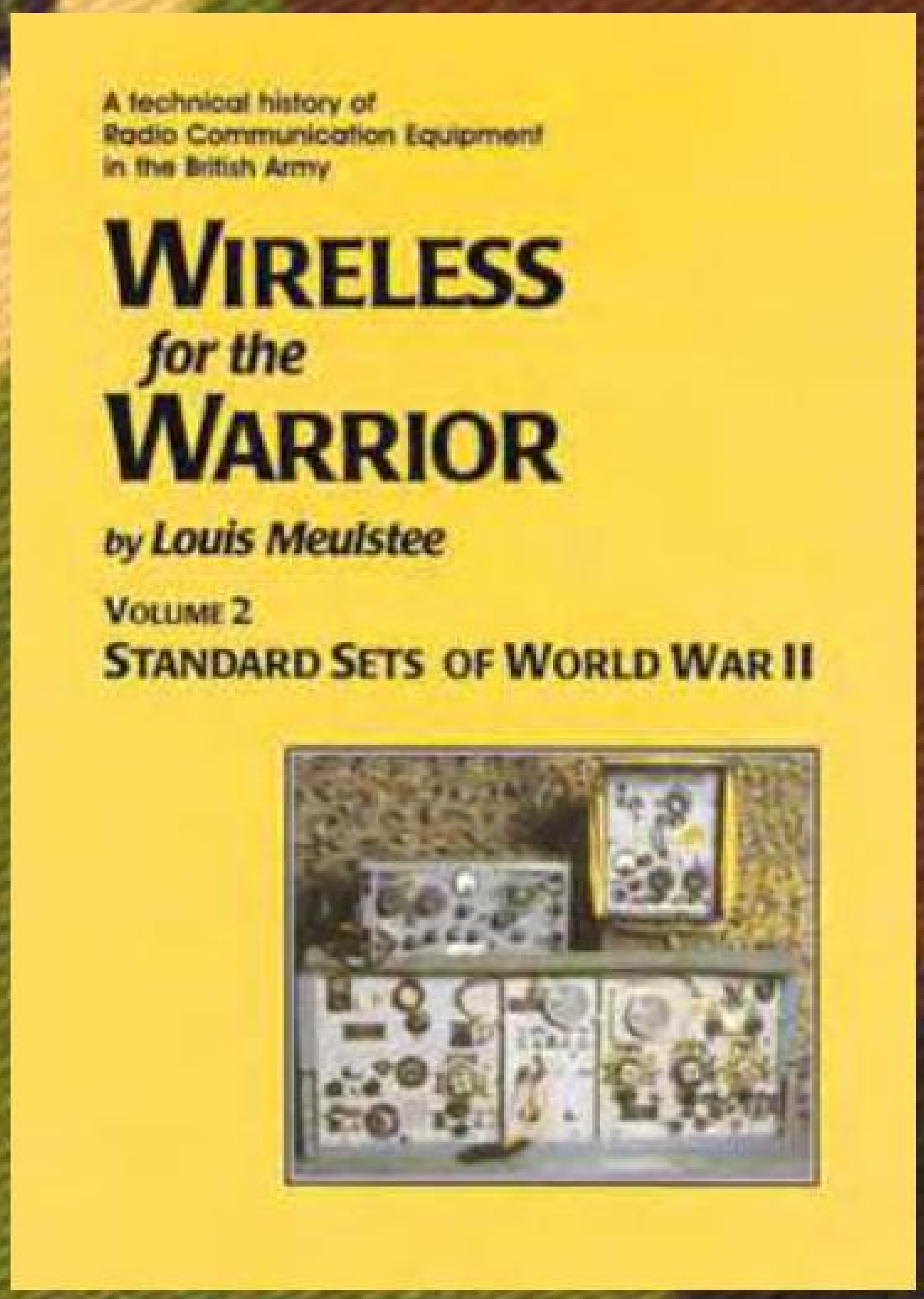

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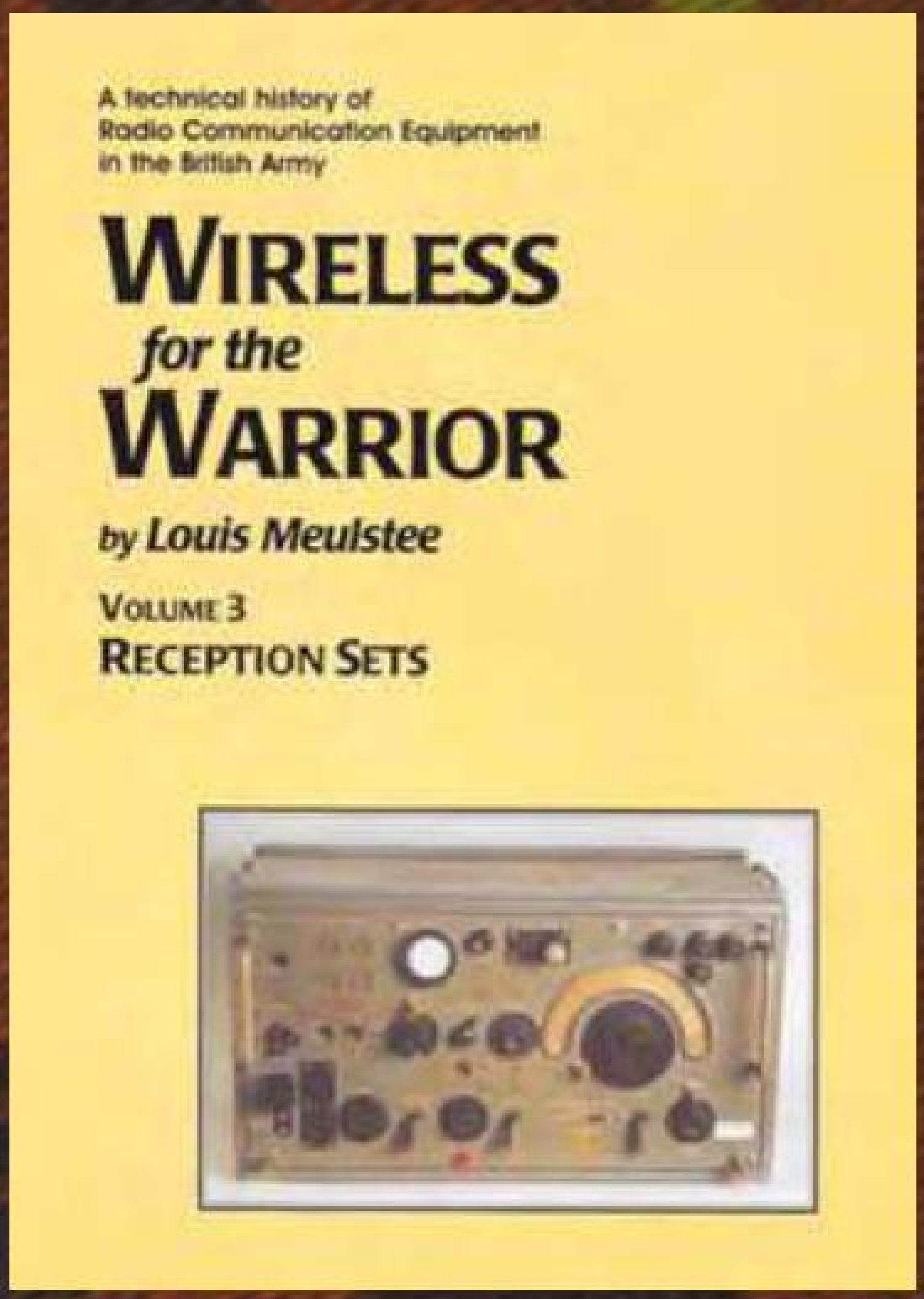

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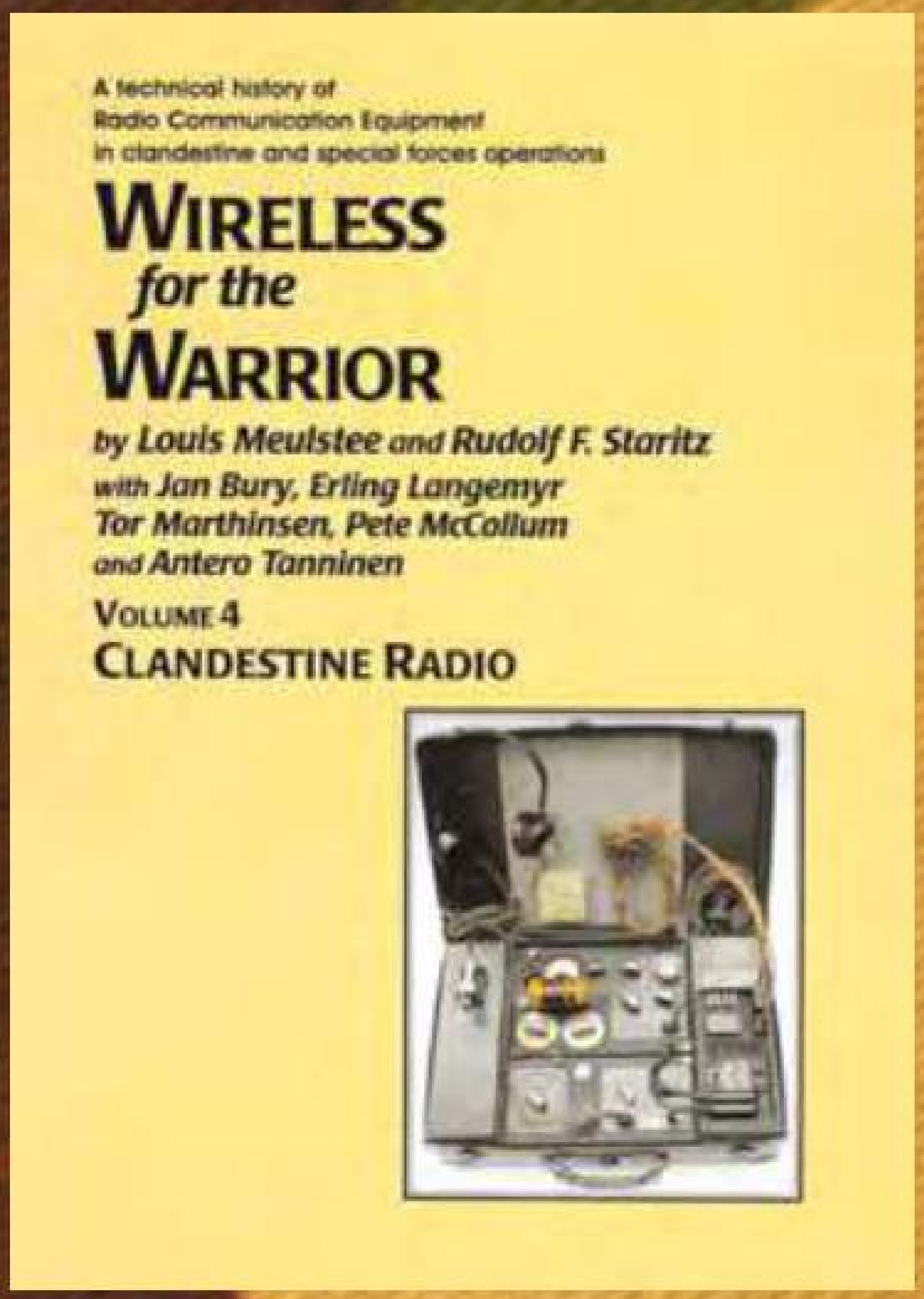

A technical history of Radio Communication Equipment in clandestine and special forces operations

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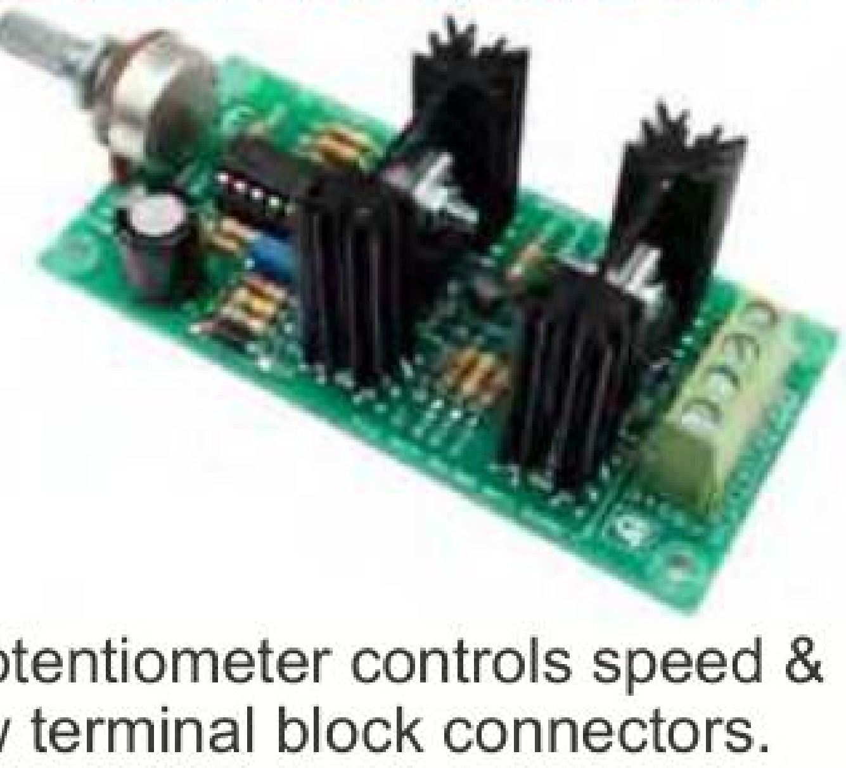

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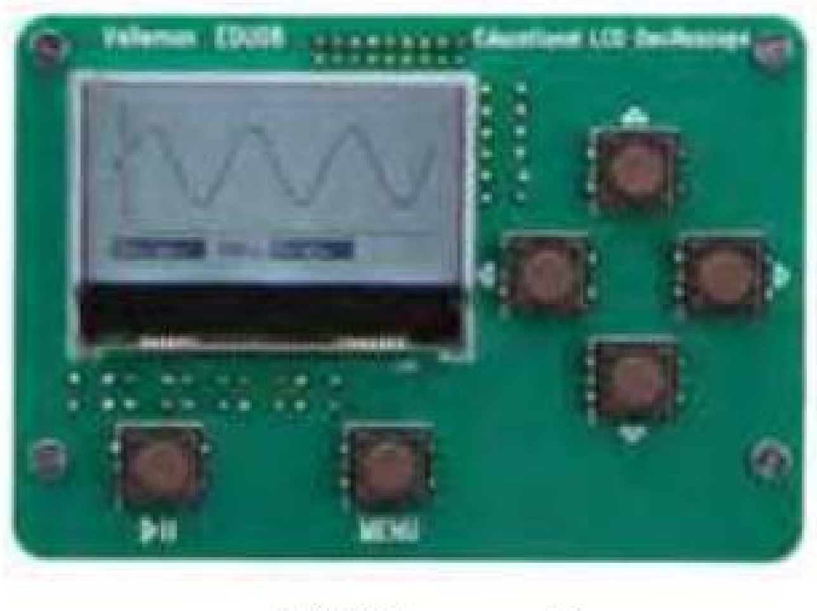

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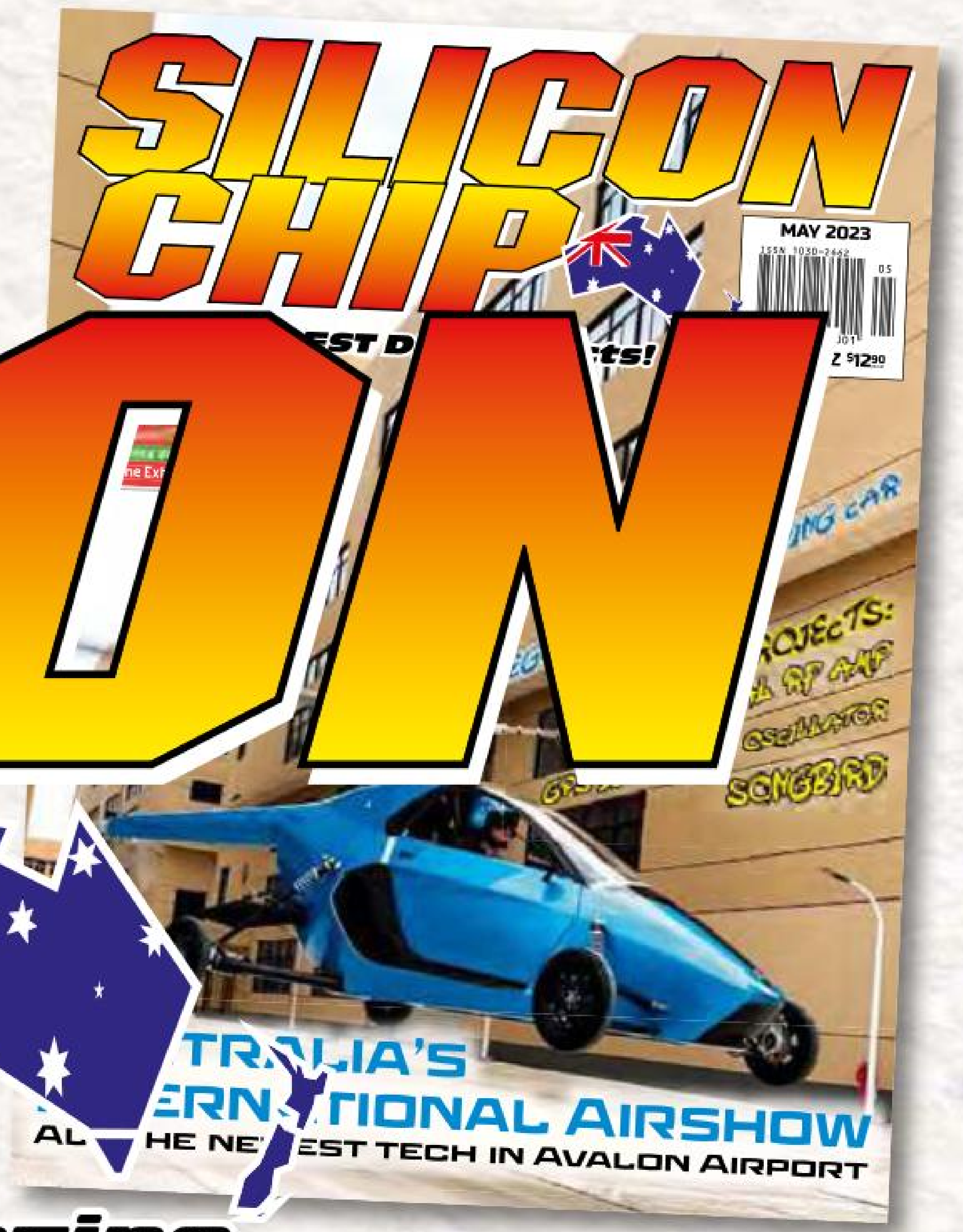
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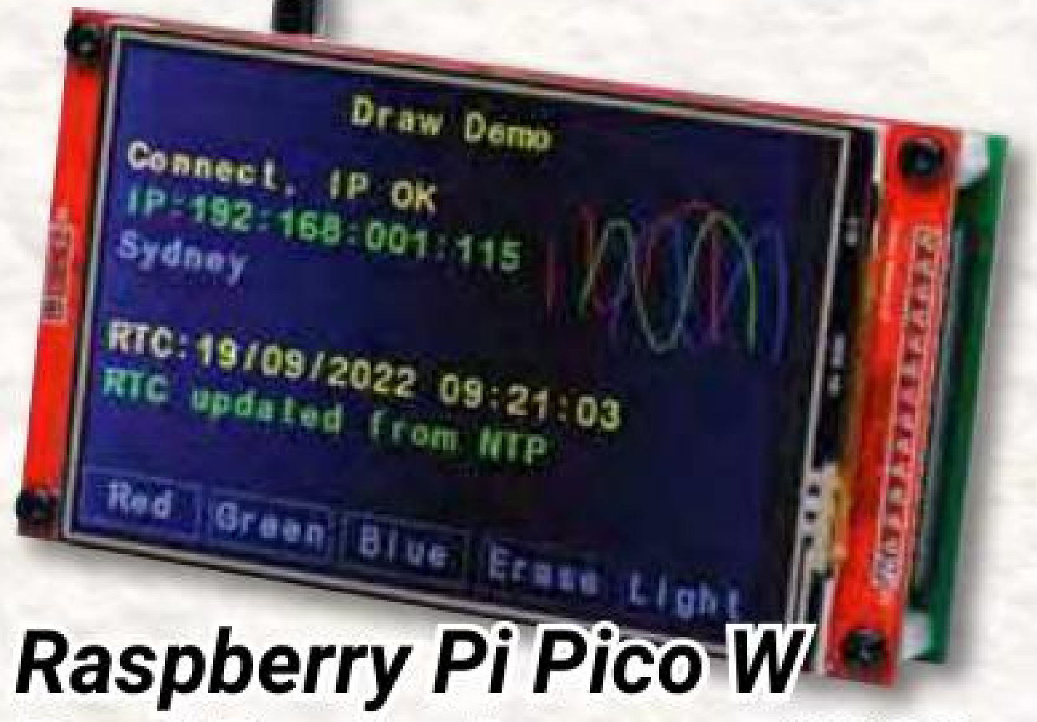
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Connect, IP OK
IP:192:168:001:115
Sydney
RTC:19/09/2022 09:21:03
RTC updated from NTP
Red
Green
Blue
Erase
Light

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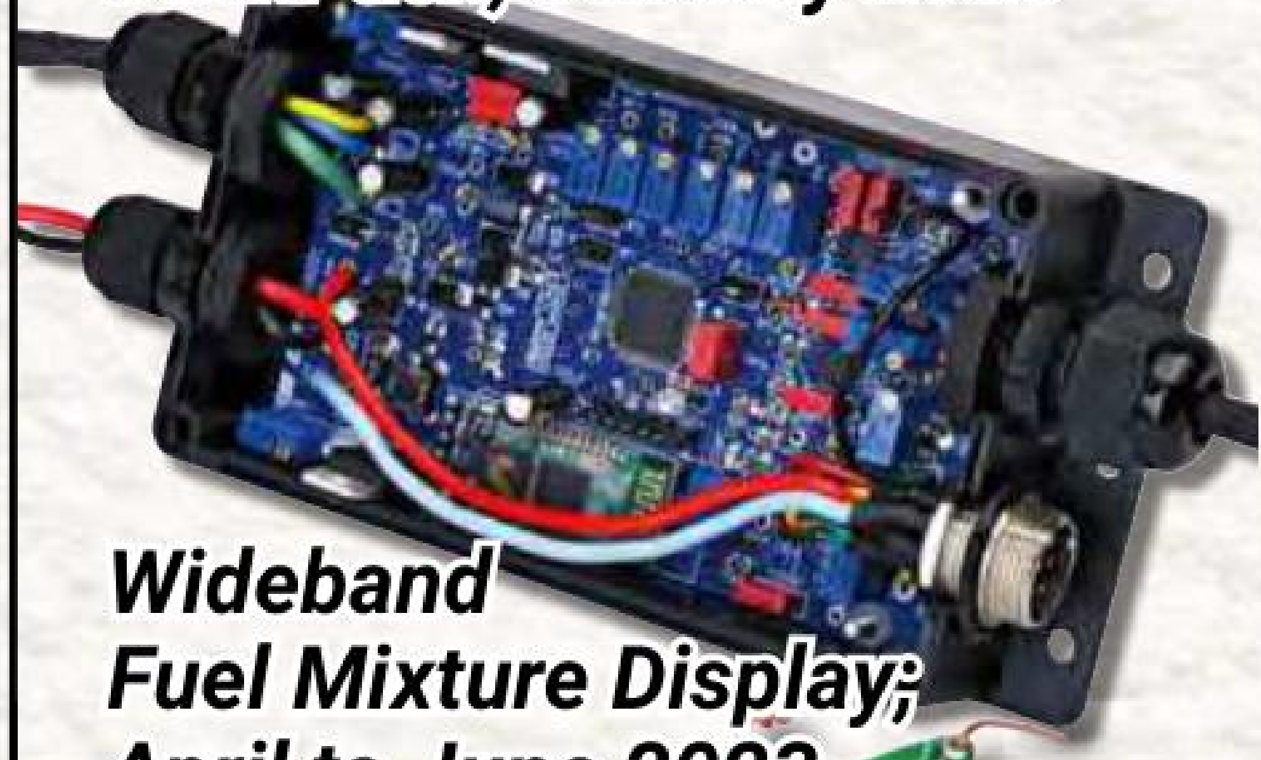

Wideband Fuel Mixture Display; April to June 2023

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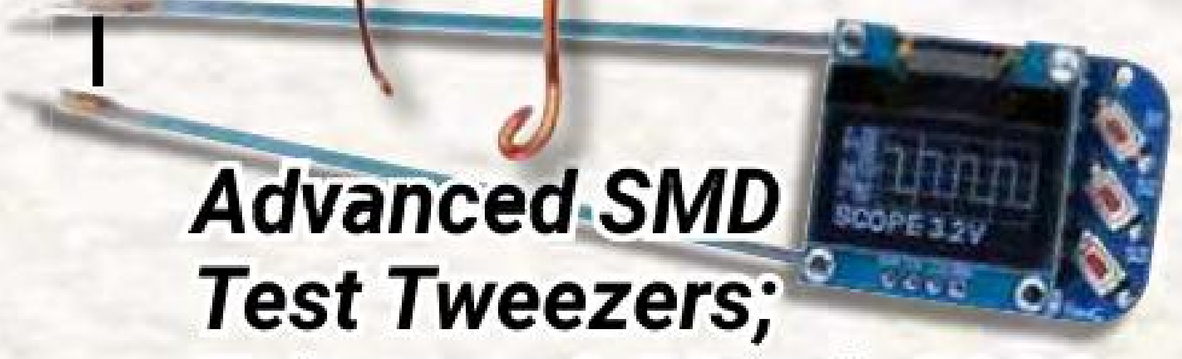

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Editorial

Powerful projects

I didn't plan it this way, but most of our projects this month seem to have a 'power' theme: a programmable load, 500W amplifier and high-current LED driver. Given the voltage and current levels floating around in this issue, it's well worth reminding readers of a few basic safety hints, tips and rules. Probably the most important one is if you don't know, then ask someone who does. This is especially true for anything involving the mains. We all start off knowing very little, and if you're not sure how to rate a fuse, earth (ground) a project properly or select the right cable then there is absolutely no shame in asking someone who does know the answer. Don't guess and don't cut corners – at best, you may ruin all the time and money you've invested in your project; at worst, you may cause a fire or give yourself a nasty shock. Electronics is rewarding and fun, but electricity must always be treated with respect and caution.

Scratching a living from audio

Audio Out this month starts a short series on troubleshooting the humble potentiometer as a volume control. As Jake explains in the introduction, his first earnings from audio electronics came from fixing scratchy pots, and while this might seem like a simple problem to fix there is actually some clever and useful electronics involved in pot-based volume control. I think you'll enjoy Jake's unique insights and observations.

Looking for a meter?

We don't do a great deal of product reviews in *PE*, but every now and again we come across a product that we think readers will appreciate and so we give it an honest appraisal. This month, Julian Edgar looks at the EEVBlog 121GW multimeter. Julian is a full-time author/engineer with interests as diverse as audio and automotive design, plus he's even designing his own smart home. If he finds a multimeter up to the job then I'm sure it's well worth putting on your short list if you're in the market for a new meter.

Matt Pulzer
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Questions about articles or projects should be sent to the editor by email: pe@electronpublishing.com

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Technology comes in different shapes and sizes

Techno Talk

Max the Magnificent

What constitutes high versus low tech evolves over time. Can you conceive the confused conjectures that could have commenced if a band of Stone Age wanderers stumbled across a time traveler's cache of glass marbles, for example?

These days, we're accustomed to hearing the term 'high tech,' short for 'high technology,' but what does this actually mean? In fact, this phrase, which may also be referred to as 'advanced technology' ('advanced tech') or 'exotechnology' essentially means the highest form of technology *currently* available. It can also be defined as either the most complex technology obtainable or the newest technology on the market.

The obvious opposite to high tech would be 'low tech,' but this is a bit harder to pin down (and don't get me started on big tech, small tech, retro tech, slow tech, and wild tech). Some people regard low tech as referring to pre-industrial revolution machines like windmills and sailboats. More generally, the *Cambridge International Dictionary of English* defines low tech as a technology that is 'not recent or uses old materials.' A more nuanced definition of low tech extends to new, future-oriented techniques that are more environmentally and ecologically sensitive.

For the engineer in me, it's tempting to categorise low tech as referring to simple, traditional, mechanical technologies. On this basis, we might class slide rules as being low-tech calculating devices, which isn't to say that they aren't incredibly clever. From another perspective, today's high tech is tomorrow's low tech. When vacuum-tube-based electronic devices like radios first appeared on the market in the early 1900s, they would have been classed as high tech (well, maybe not, because the 'high tech' nomenclature wasn't coined until a 1958 column in *The New York Times*), but most of us would now class these cunning contraptions as falling into the 'low tech' category.

That's nuts!

The reason I'm currently cogitating on this topic has its origin in the mid-1980s when the small company I was working for designed a hardware accelerator for UNIX computers. This was a box around the size of a small UK refrigerator that sat next to the main UNIX machine. Our accelerator could offload the main machine and speed some applications by one or two orders of magnitude.

Eventually, we sent our masterpiece off to a special laboratory to have it tested for its resiliency to vibration and shock, and to be certified for use in industrial environments. It failed. According to the report, the accelerator was DOA (dead on arrival). On its way to the lab, the machine nuts attaching the top-mounted cooling fan had vibrated loose, allowing the fan to fall into the guts (well, brains) of the machine. Suffice it to say that we ended up wearing our sad faces that day.

This all came flooding back to me when I ran across a nice video about something called Nord-lock washers (**https://bit.ly/3zXrxcZ**). Prior to seeing this little scamp, I would have classed machine screws and nuts and washers as being low tech. All I can say is that I now look at washer technology with new respect. I haven't felt this excited since I was introduced to the concept of a one-way Tesla valve that allows water (or another fluid) to flow one way and blocks it from flowing the other way, all without any moving parts – see: **https://bit.ly/3GLw71F**

You can tell me that both these devices are low tech as much as you want, but they impress the socks off me!

Losing my marbles

When I was a kid, I used to enjoy playing with glass marbles. I also used to enjoy simply looking at them. Some had swirls of color, others contained small bubbles of air, and each was a delight in its own unique way.

I'm sure that the machines used to create glass marbles would be classed as being low tech, and that may be true, but if you were tasked with designing a machine to make marbles, would you be up to the task? To be honest, I wouldn't have known where to start until I ran across a very cool video that explains all: **https://bit.ly/43zJbAY**

Triangles, tiles, and mazes (Oh my!)

A few days ago, as I pen these words, I started to hear tales racing around the interweb that two high school students had come up with a new proof of the Pythagorean theorem (you know the one, $a^2 + b^2 = c^2$). Initially, I was somewhat underwhelmed, but then I started to think about how I would go about generating such a proof. It didn't take long before I wanted to learn more, so I found a video that explains all. All I can say is that Pythagoras would be proud: **https://bit.ly/3MLxGAA**

On the one hand, you can't get much more low tech than tiles (think ceramic tiles covering a bathroom floor). Of course, actually making tiles is a lot harder than talking about making them (I know because I have my own kiln that I'm using to make tiles for a monster mosaic, but that's a story for another day). I just heard that an amateur mathematician has discovered a 13-sided tile that can cover a surface without ever creating a repeating pattern – see: **https://cnn.it/41q1iYO**

The problem with YouTube is that you keep on getting sucked into metaphorical rabbit holes. For example, I also ran across a fascinating video showing how water can be used to solve a maze: **https://bit.ly/41JVfOa**

Reinventing the wheel

People say that you shouldn't waste your time reinventing the wheel. What they fail to mention is that you may end up creating a revolutionary new rolling device. Last year I was introduced to an example where someone managed to use two half wheels to perform the task of a full one: **https://bit.ly/3KORUqA**

More recently, I saw a video of someone sitting on what appeared to be a normal bicycle equipped with two square wheels. When the bike's creator mounted the beast, I was expecting a painful viewing experience, but I was blown away by what I saw: **https://bit.ly/3osHuW3**

Amazingly, one of my friends found the perfect complementary clip from the 1964 British 'historical' comedy film *Carry on Cleo*. Make sure to watch to the very end because the last line is the corker: **https://bit.ly/3otsEP7**

Exclusive offer

Win a Microchip CryptoAuth Trust Platform Development Kit

Practical Electronics is offering its readers the chance to win a Microchip CryptoAuth Trust Platform Development Kit (DM320118) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The CryptoAuth Trust Platform is a compact hardware evaluation kit that can be used with the Trust Platform Development Suite (TPDS) and other software tools. This kit is used for exploring and implementing solutions for the IoT space with a pre-provisioned ATECC608B Trust&GO, pre-configured ATECC608B TrustFLEX and fully customisable ATECC608B TrustCUSTOM products. The Trust&GO and TrustFLEX products have been developed to allow for an easy way to add hardware security to IoT Cloud solutions, accessory authentication, IP Protection and firmware verification.

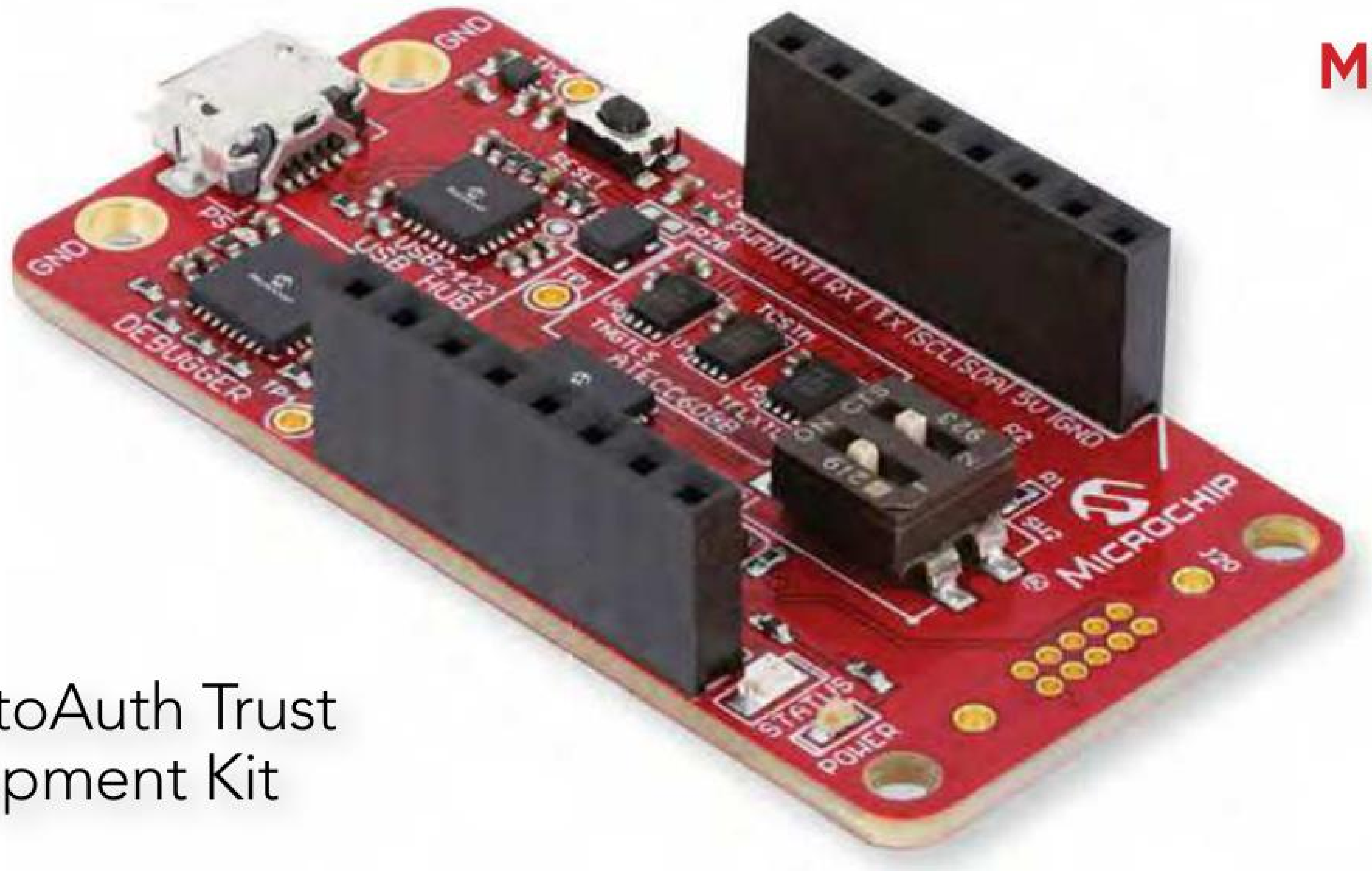
Worth $24.00 (approx £20.00) each

Using these kits with the Microchip development tools and Microchip provisioning systems allows for even low-volume projects to easily implement secure authentication into their application. The user guide provides a physical overview of connections, components and switch settings implemented on the board.

The CryptoAuth Trust Platform consists of an ATSAMD21E18A, operating as the main MCU, which comes pre-programmed with Microchip's Secure Product Group (SPG) kit protocol. A low-power, high-performance Microchip ARM Cortex-M0+ based Flash microcontroller, the ATSAMD21E18 is ideal for a wide range of home automation, consumer, metering and industrial applications. This protocol takes care of the communication between the CryptoAuthentication devices and the host MCU over the USB HID interface. The data transfer between the secure elements and the host MCU is indicated by the status LED.

The kit supports mikroBUS for easy connection to MikroElectronika add-on boards such as the EV92R58A Development board, which is an accessory board for evaluating the ECC204, a new member of the CryptoAuthentication product family. The device is targeted for disposable and ecosystem control applications, and is intended to be used as a companion device with Microchip or other vendors' microcontrollers.

Free-to-enter competition



Microchip DM320118

Microchip CryptoAuth Trust Platform Development Kit

How to enter

For your chance to win a Microchip CryptoAuth Trust Platform Development Kit or receive a 15%-off voucher, including free shipping, enter your details in the online entry form at:

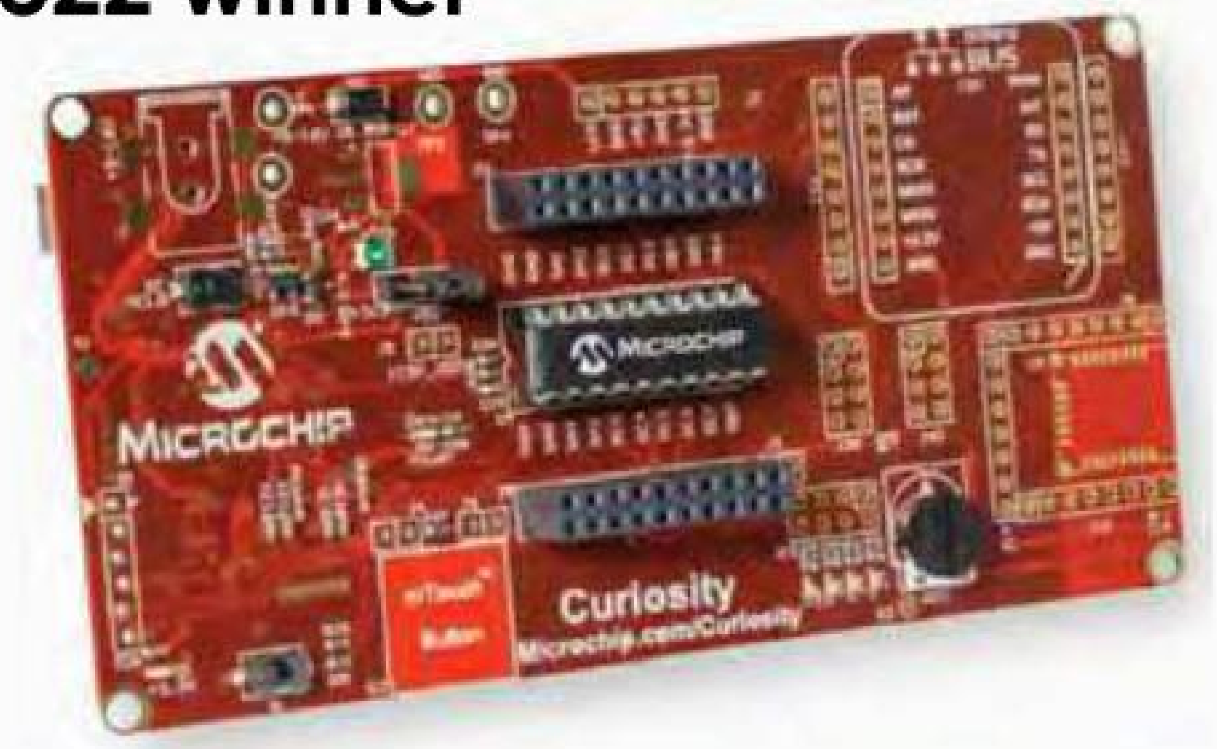
https://page.microchip.com/PE-Crypto.html

Closing date

The closing date for this offer is 31 May 2023

February 2022 winner

Andrew Reid



He won a Microchip Curiosity Development Board

Net Work

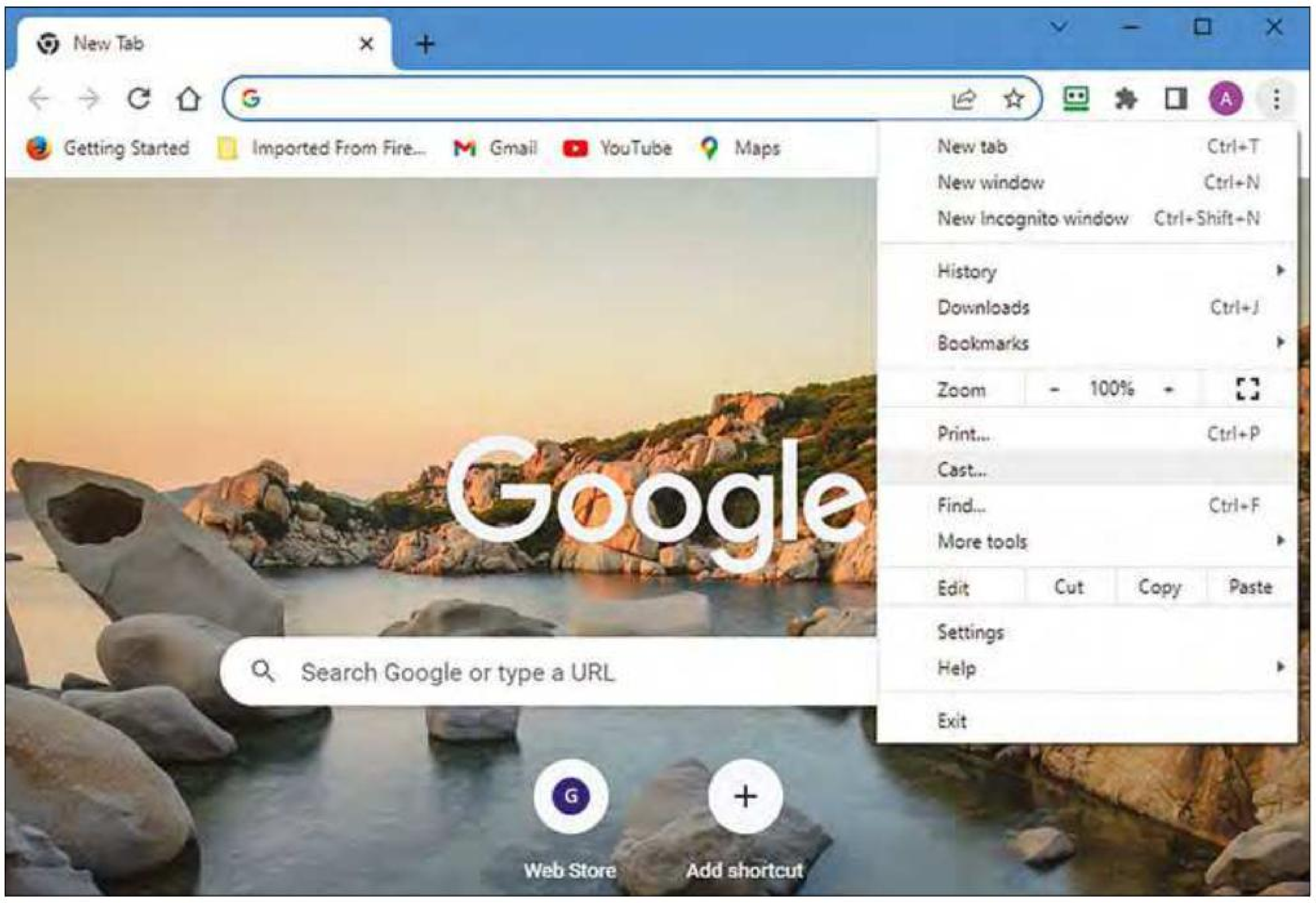
Alan Winstanley

This month's Net Work highlights practical problems with online payments, and we investigate some 'dark patterns' that try to manipulate our online behaviour and choices. Plus, we visit some live auctions!

A few weeks ago, I found myself helping an elderly lady to shop for a house insurance policy, so naturally I went online in search of the best deal. The lady lives in a remote farm, so she has neither Internet access nor a mobile phone. After collecting her from the farm, I started off by 'casting' some insurer's web pages from my laptop onto my smart TV in the lounge. This way we could view some insurance quotes and offers together. So far, so good. (All the major web browsers can cast to a smart TV this way, eg click the 3-dots More icon, then choose Cast. A Google Chromecast HDMI dongle is an easy way of making a TV network-ready).

The first hurdle when looking online for quotes was that the lady had no email address, so I used my own instead. After we plumbed for one insurer, next came the secure payment page which called for debit card details. No problem there either, until the two-factor authentication (2FA) applet popped up demanding to send (SMS) confirmation to the lady's phone number. My heart sank when I realised that details of her *landline* number were showing onscreen. At this point my cunning plan crumbled, because obviously I couldn't collect the 2FA call over on the farm's landline.

So we rushed back to the farm again where, using my smartphone as a Wi-Fi hotspot, I managed to hook up my laptop to the web, and I punched in the debit card details again and waited expectantly for the 2FA call to come through. I'd hoped that maybe BT's SMS to Speech service would call the landline and robotically read out a PIN number or something like that, but there was no such luck and inevitably a long phone call to an overseas call centre followed. Ultimately, I personally had to jump through some ID hoops of my own to allow my own mobile number to be added to the lady's bank account details. After one last try, the 2FA text finally arrived on my own mobile phone and the transaction was completed.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Print... Ctrl+P
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Help
Exit
Google
Search Google or type a URL
Web Store
Add shortcut

Web browser pages can be cast onto a smart TV on the same network by using the browser's More... Cast menu.

Never knowingly uninsured

The drive towards going 'paperless' then saw an 80-page PDF insurance policy (and more besides) land in my In Box, but an all-important hard copy was promised in the post. To its credit, the insurer (John Lewis / Munich Re) was the only one that made it very

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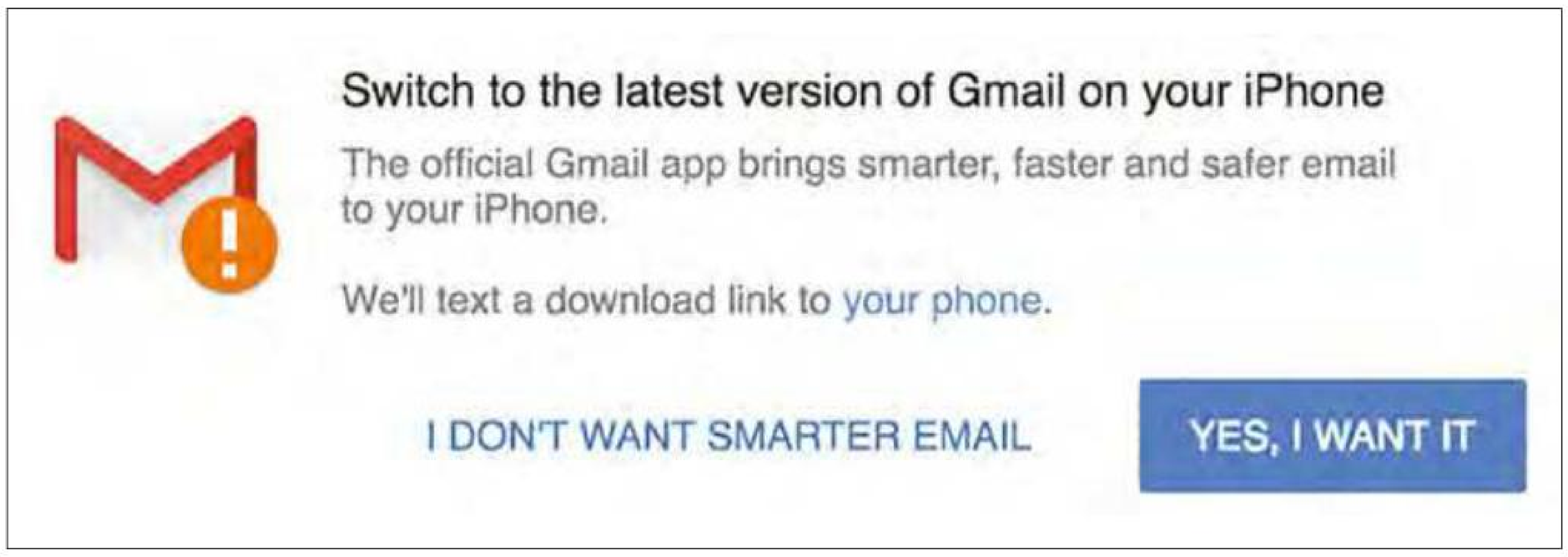
A smartphone, when paired to the car's dash, allows the car's web browser app to go online when parked. Other methods include using Android Auto, depending on compatibility.

simple to assign policy management to a trusted third party such as myself (equipped with web and email), which would let me deal with future issues online on her behalf.

This episode illustrated some of the technological hurdles and 'gotchas' that even the most organised people face when trying to carry out routine business online. The underlying assumption is that everyone has access to a smartphone or PC, email, a PDF reader and 2FA all set up and waiting. Without these things, conducting one's business becomes much more difficult. Early efforts to set up telephone banking in lieu of online banking also stalled, with National Westminster Bank's website stating that the easiest way to set this up was to go online!

Elsewhere, the lurch towards a cashless society shows no sign of abating. In Britain it's reported that increasing numbers of town councils are doing away with 'Pay & Display' car parking machines (ones that accept coins) in favour of forcing motorists to use apps instead.

One key reason is that legacy 3G-based datacomms used by ticket machines are being wound down and councils can't afford to upgrade them. Some more enlightened authorities offer app-based parking alongside coin-based machines that print proper tickets, which is probably the best compromise. The website 'In Your Area' has more to say on this at: **https://tinyurl.com/n8runjdx**



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The official Gmail app brings smarter, faster and safer email to your iPhone.

We'll text a download link to your phone.

'Confirmshaming' is a dark pattern ploy used to 'guilt-trip' or 'shame' users into making an affirmative choice. (Image: deceptive.design)

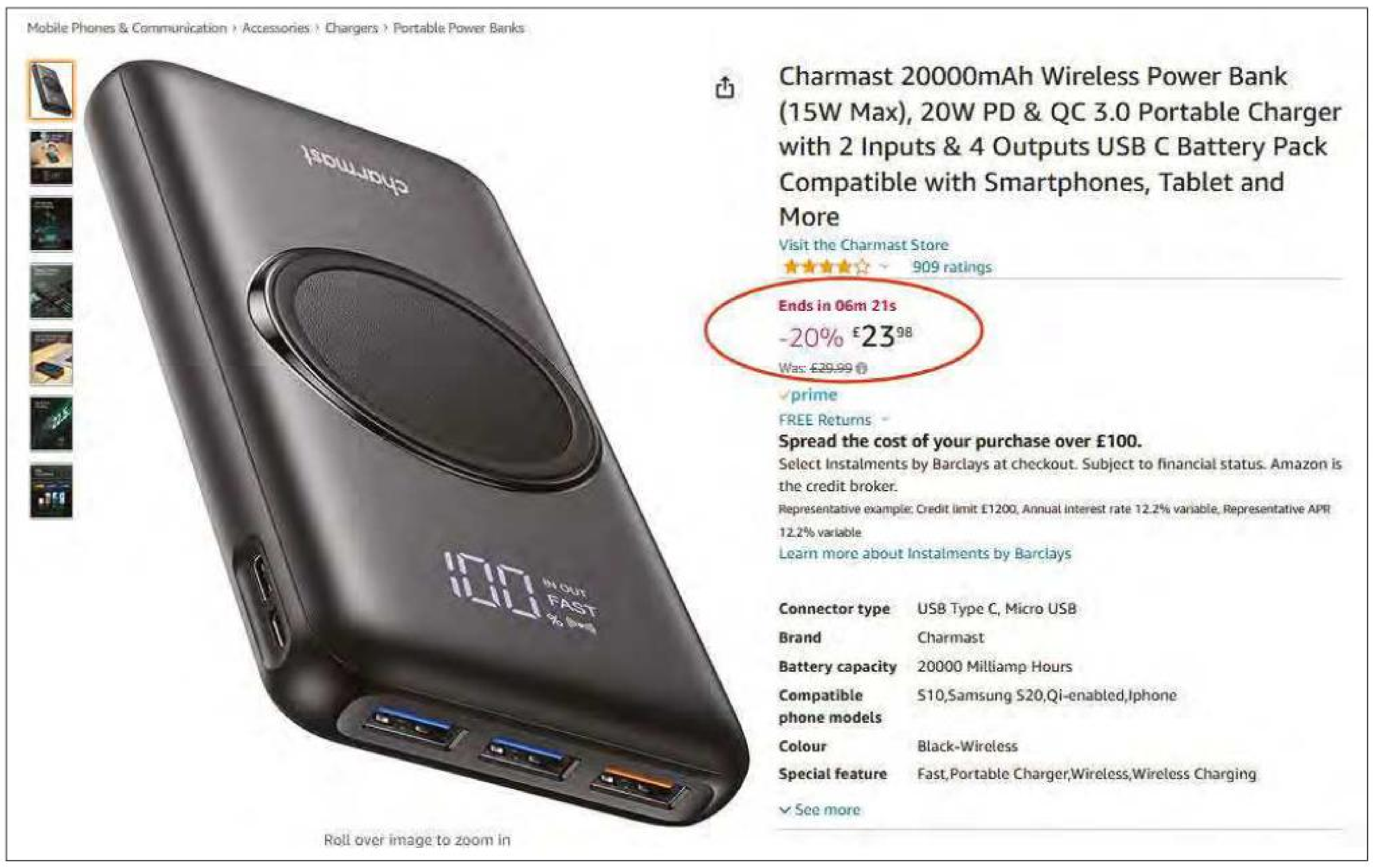
Admittedly, I like the convenience of paying using the MiPay app from inside my car, even if it costs me 10p for the privilege. With this comes yet another problem: there are a multitude of different car parking apps in use (30 or so), so you have to install and register your car and debit card with the one used by your local authority – hassle that only deters older people from using smart technologies like these. My elderly friend gave up entirely when I showed how I could pair my smartphone with the car's entertainment system, and watch YouTube channels on the car's web browser while we were parked.

The moral of the story is that as the drive to online transactions accelerates, groups of people risk getting left behind. Factors such as age, location, education and limited resources lead to low or no online presence and the result is exclusion from choices and services we take for granted. It's not just a question of access to kitten videos or TikTok dance memes, but vital services from insurance and banking to on-street parking, everyday shopping and passports.

Dark Patterns of behaviour

We've all grown used to buying online and using the web for all manner of things. Likewise, online sellers and marketers have developed all sorts of hidden and deceptive methods to steer website users down a particular route, highlighting some options while downplaying others or omitting them altogether. The term 'dark patterns' is fast catching on to describe techniques used by websites, apps or software to influence or manipulate a user's behaviour into doing something they might not otherwise do (usually, signing up or buying something or giving out information). America's Federal Trade Commission published an interesting précis of a 'dark patterns workshop' event held back in 2021, which you can read at: **https://tinyurl.com/2p8vm46c**

The UK's Consumer's Association (CA, publishers of the well-regarded *Which?* magazine) summarised the eight most-used dark patterns that are designed to urge online users into making a choice. *Net Work* readers will certainly recognise them, including a pressing 'Activity message' pop-up such as, 'David from Manchester just bought a gadget!', hoping that you will get carried along by the shopping frenzy. Then there's the 'High-demand message,' warning that a product or service is in high demand and/or likely to sell out soon. 'False



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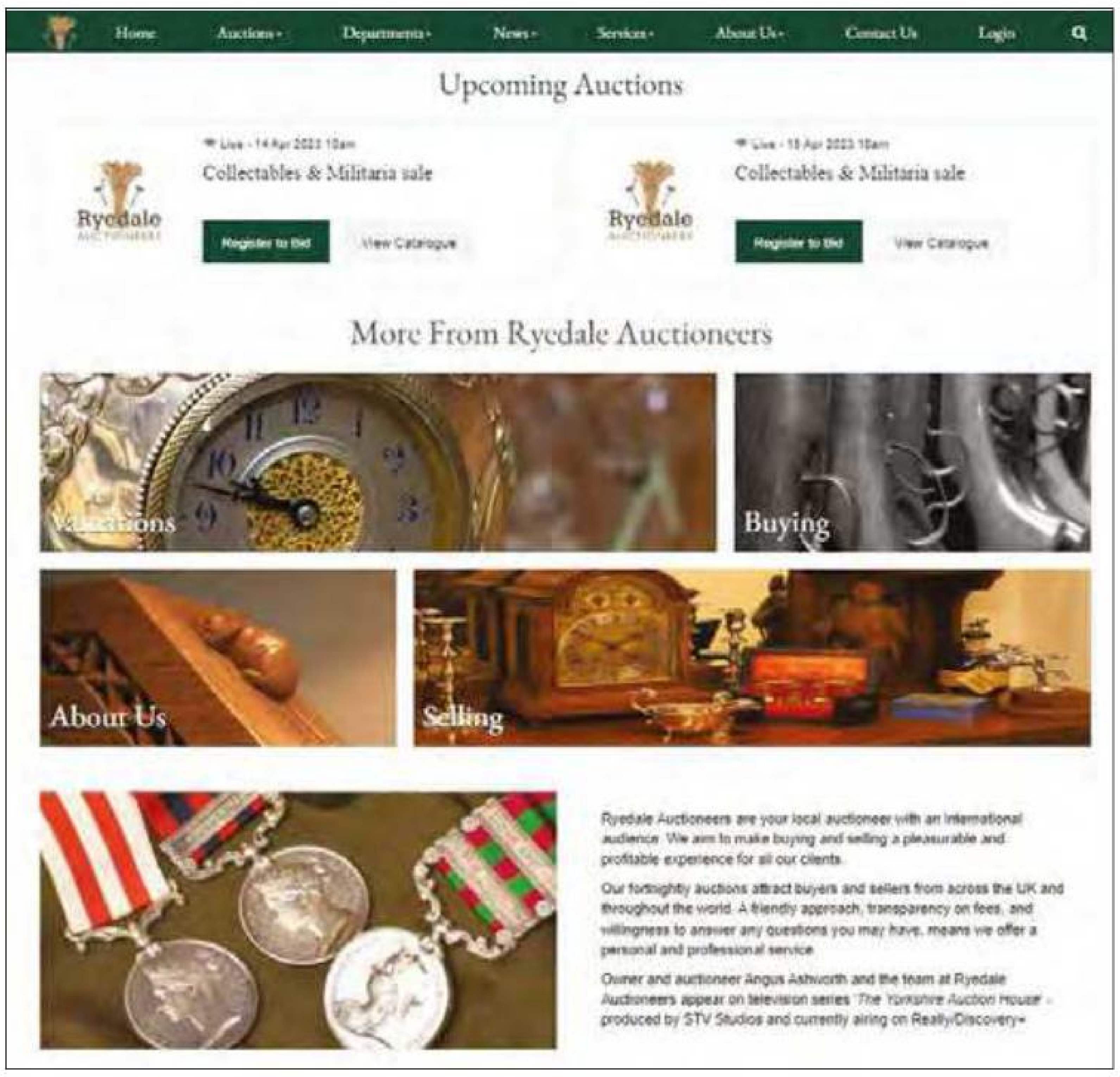
Colour	Black-Wireless
Special feature	Fast,Portable Charger,Wireless,Wireless Charging

See more

Amazon 'Lightning Deals' use 'dark pattern' countdown timers to whip up more trade.



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Our fortnightly auctions attract buyers and sellers from across the UK and throughout the world. A friendly approach, transparency on fees, and willingness to answer any questions you may have, means we offer a personal and professional service.

Owner and auctioneer Angus Ashworth and the team at Ryedale Auctioneers appear on television series *The Yorkshire Auction House* - produced by STV Studios and currently airing on Really/Discovery+

The Yorkshire Auction House, as seen on TV, is one of many auctioneers offering live auction feeds over the web. Thousands more are listed via auction aggregator web portals.

hierarchy' emphasises one choice over another by means of the user interface (UI) design.

More insidious is 'Confirmshaming,' which tries to guilt-trip users into making a choice: notably, the act of refusing the offer is designed to 'shame' the user into accepting it instead. For example, instead of displaying 'Dismiss or 'Cancel' buttons an online fill-in form might show links or buttons labelled 'No, I don't want to save money' or 'No, I don't want smarter Email'. Other dark patterns include a countdown timer indicating when a deal will expire: Amazon 'Lightning deals' work that way, but Amazon customers expect it as part of the package. Holiday and flight booking sites do the same, to snag more bookings.

Smart online consumers are gradually learning how to recognise this manipulative design behaviour. The leading expert on 'dark pattern' design is the English independent consultant Harry Brignull, who has campaigned against and exposed many unethical dark patterns. You can learn more at the website: **www.deceptive.design**

Having a good sort-out

Springtime usually brings with it the urge for some domestic spring cleaning, de-cluttering and generally having a good old-fashioned clear out. It can be a liberating experience and websites such as eBay, Ziffit, musicMagpie and Vinted are convenient ways of selling off old stuff to raise some welcome cash. Ziffitt and WeBuyBooks trade in secondhand books, and their smartphone apps will scan barcodes and offer a price, subject to sight of the book. Parcels of books are then collected from your door. Some customers say that books might fetch only a few tens of pence or they might be scrapped upon receipt due to their condition, with no apology or payment being made. Even so, it's a convenient way of recycling books rather than throwing them out. Amazon stopped its Book Trade-In service but start-up booksellers might try registering as a seller on Amazon as a sideline, sourcing used books from friends, jumble sales or charity shops, see: **https://bit.ly/pe-jun23-sell**

The Vinted website sells clothing and fabrics, and the Vinted app makes it easy for sellers to upload their listings. The reason Vinted is *free to sell* is because *buyers are charged* a compulsory 'Buyer Protection' fee costing £0.30 to £0.80, plus 3-8% on top. To quote their terms, Vinted, 'does not sell or buy items shown on the site and is not a party to any transaction between users' – more on that aspect in a moment.

Other websites trade in electronics, music CDs, DVDs and tech, but it seems people will buy or sell just about anything on eBay. The process of listing items for sale on eBay has become complex and onerous, especially for simple occasional sales as there are myriad options and check-boxes to wade through, but if you have a regular stream of goods to sell then it's worth investing some time in getting to understand the choices available. Apart from uploading up to 24 photographs, you can now add a video on eBay sales as well.

Studer Breaker

eBay's 'reach' is unparalleled but one recent news item really raised my eyebrows: it was reported that Mike Godden, a retired British music studio manager, tried selling his rare Studer A80 tape recorder on eBay, and bids started to flood in. He reportedly then discovered a fault in the tape deck, so with eight days still to go he cancelled the eBay auction, something that the eBay system entitles him to do unless it's due to finish within 12 hours. Bidding had reached £1,380 ($1,680) by then. However, Mr. Godden's problems had only just begun: the leading bidder was from Germany, and he declared the tape deck was rightfully his, and he still demanded the goods.

Unable to deliver the tape deck as advertised, things would not go well for Mr Godden. Unwilling to compromise, the German buyer then sued Mr. Godden in the German courts for breach of contract. Thanks to some arcane legal technicalities, the German court held that under EU law, which currently still has primacy over UK law in many areas, a binding contract existed between the two parties (under the EC Rome I Regulation, for anyone interested). Mr Godden, appearing in court by video link, was ordered to compensate the German buyer to the tune of £7,551 ($9,200) being the equivalent cost of a used Studer A80. Legal costs hiked up the bill to £11,600 ($14,150) which, incredibly, Mr Godden had to cough up in full.

Despite complying with eBay's own rules for cancelling the auction, Mr Godden had no redress against the online marketplace. The eBay User Agreement spells out why: 'eBay does not have possession of anything listed or sold through eBay, and is not involved in the actual transaction between buyers and sellers. The contract for the sale is directly between buyer and seller. eBay is not a party to the transaction and is not a traditional auctioneer.' So the German buyer was entitled to pursue the civil matter through the courts, which is what he did. eBay warns bidders that they're entering into a legal contract when bidding. Therein lies a warning to anyone in the UK selling to EU member states (or even elsewhere in the UK, for that matter), and doubtless the high value of the tape deck sparked this unfortunate legal action.

Going once...

Rather than selling on eBay with all its attendant risks and pitfalls, there's always the option of using traditional auctioneers instead. Local auction houses are buzzing with trade and, thanks to the advent of online access, it's never been easier to watch or participate in real-time auctions conducted by reputable bricks-and-mortar auctioneers. Some readers might follow the popular TV series 'Yorkshire Auction House' featuring auctioneer Angus Ashworth (showing on Discovery+, Really TV). Recently, I had the great pleasure

The SpaceX Starship is the largest rocket ever built. Shown fully stacked at Starbase in April, ready for its first integrated flight test. (Image: SpaceX/ Twitter).

of letting Angus auction off some lots on my behalf. Auctions are often broadcast on the web (sometimes with sound only); so, along with some friends, I tuned in online to listen to Angus doing his stuff at a country house auction. It was the next best thing to being there, and I must admit the live sale was a bit heart-stopping at times!

Well-known 'aggregator' auction services include 'The Sale Room' (**www.the-saleroom.com/en-gb**) and the website 'Easy Live Auction' (**www.easyliveauction.com**) which offer an online front-end for many thousands of auctions being held around the world, and they also handle back-office operations as well. It's easy to drop in on an auction without registering, and sometimes the excitement of seeing lots going under the hammer can be more interesting than watching TV… if you like that sort of thing. There are often many hundreds of lots to get through in a session, and one can only admire the stamina of the auctioneer who has to plough through them all. For added tension, a rapid-fire 'timed auction' runs against the clock.

Auction catalogues can be studied online beforehand, and if anything catches your eye you can register online as a buyer with any particular auction house. High-speed broadband sometimes makes for fast and furious online bidding. (Incidentally, eBay bidders can try AuctionStealer or Bidnapper for last-minute 'sniping'.)

In case you're not aware, auction fees are payable by both buyers and sellers, say 20% + VAT or more – see: **https://bit.ly/pe-jun23-tsr** – and a small insurance premium is charged to sellers to cover any liabilities. Sellers are only paid once the buyer completes the deal, so there's always a remote risk of sales falling through. Buyers must then arrange to collect their winning lots or incur storage fees, although the auction house might post small items or they may recommend a local haulier. Auctioneers do battle hard to provide the best service as they want to retain happy sellers and bidders but, as with all things, check the Terms & Conditions carefully. The name behind the Yorkshire Auction House TV series is Ryedale Auctioneers based at Kirkbymoorside, North Yorkshire, and upcoming auctions can be viewed at: **www.ryedaleauctioneers.com** – I tune in every fortnight!

Other news

They say that life can turn on a sixpence: in other words, events can change radically in the slightest instant. So, it's enormously saddening to report that Virgin Orbit has ceased operations following the aborted attempt to launch satellites into orbit from Cornwall in England earlier this year. *Net Work* has charted the progress of Virgin Orbit since September 2021 after they used a 747 to put an array of satellites into LEO (low earth orbit), using an ordinary runway instead of a vertical launch pad. As readers know, the Cornwall 'Start Me Up' mission sadly ended in failure, most likely because of a faulty fuel filter. Virgin Orbit is now seeking Chapter 11 protection while attempts are made to sell the business. It would be a terrible shame to lose this expertise, but the only hope left is that another space programme might buy the know-how and assets and take the concept forward.

Meantime, Elon Musk's SpaceX company is moving on with its most ambitious project ever, the Starship super-heavy lifter. Starship has the Moon and Mars in its sights, and with up to 33 engines it is the largest, tallest, most powerful rocket ever built.

Just before we went to press for this issue, the test rocket, which had been fully built-up on its Texas launch pad, was sent on its maiden flight. SpaceX had tried to dampen expectations, saying that simply getting the vehicle off the ground without destroying the launch pad site would be viewed as 'a win'. Well, they certainly did that, but according to SpaceX engineers, three minutes into the flight, 'Multiple engines on the 33-engine booster were not firing as the rocket ascended, causing it to lose altitude and begin to tumble. The rocket was intentionally destroyed by its self-destruct system, exploding and plummeting into the water'. With impressive engineering-speak

Despite a successful lift off, three minutes into its maiden flight, SpaceX Starship underwent a ‘rapid unscheduled disassembly’.

Chinese luxury EV maker HiPhi is preparing plans for a launch in Britain.

understatement, the enormous Starship explosion was described as a ‘rapid unscheduled disassembly’.

Yet another Chinese EV brand might be heading to our shores, with luxury maker HiPhi planning to launch in Britain. They are aimed at high-technology lovers and cars include highly advanced features such as warnings projected onto the road, and facial recognition of drivers. The Chinese website at: **www.hiphi.com** has English pages (if not videos).

I learn that the UK electric vehicle charging network Osprey is ramping up the delivery of EV charging points, having delivered 142 new ones in just 10 weeks this year, the same number it installed in the whole of 2022, they state. A further 50 are due in April. More information can be found at: **www.ospreycharging.co.uk**

Predictably, it didn’t take criminals long to realise that valuable cables can be stolen from the boots (trunks) of EVs, or even while the car is charging up. The high-grade copper they contain can sell for £50 or more, and complete cables can fetch £200 on the black market. Domestic wall chargers themselves are also being stolen. A *This Is Money* article explains more at: **https://tinyurl.com/2jb8vz22**

The online vendor EV Cables offers plenty of technical guidance and can ship all manner of replacement cables across Europe; for more details, visit: **https://evcables.com**

It’s come to light that EV car insurers are starting to scrap EV cars that have only suffered minor damage, the *Daily Telegraph* reports. Batteries are some 50% of the car’s value and damage (eg kerbing the underside) risks the cars being entirely written off due to the sheer cost, extreme complexity and hazards involved in fixing them, which makes repairs non-viable. As reported last month, the sale of used EVs continues to plummet in Britain, with some dealers simply refusing to stock any of them.

Finally, on the topic of small modular reactors (SMRs), nuclear power plants that it’s hoped will shore up the power generation market, US supplier Last Energy (*Net Work*, June 2022) has signed deals to supply no less than 24 of their new 20MW power plants directly to UK customers through a series of trade partnerships. Details are sketchy, but buyers include a science park and a data centre developer. UK Regulatory approval is still required but Last Energy aims to start delivering within three years, they say. Ten more SMRs are also destined for Poland. This piles more pressure on Rolls Royce who have great ambitions for their own SMR, as previously described in earlier columns.

That’s all for this month’s *Net Work*. Don’t forget that the hyperlinks above are ready-made for you to click on in my *Net Work* blog summary at: **www.electronpublishing.com**

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LAMBDA GENESYS	PSU GEN50-30 50V 30A	£400
IFR 2025	Signal Generator 9kHz – 2.51GHz Opt 04/11	£900
IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

Marconi 2955B Radio
Communications Test Set – £800

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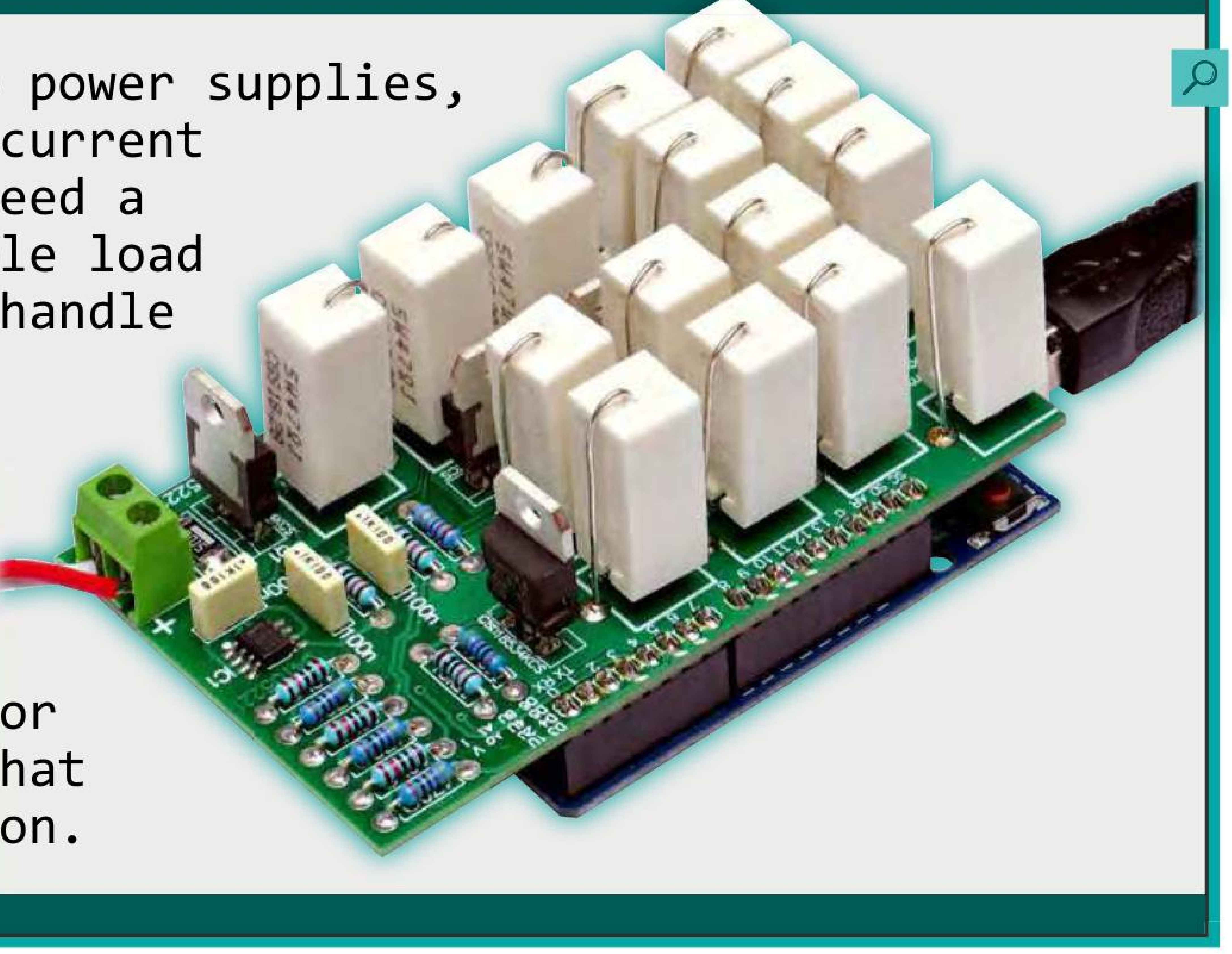
Arduino Programmable Load

Project by Tim Blythman

To test devices like power supplies, driver circuits and current sources, you often need a particular or variable load resistance that can handle a bit of power. This Programmable Load is based on an Arduino shield that is easy to understand, build and use. It can be controlled manually or automated in a way that suits your application.



During the design and testing of our *High Power Buck-Boost LED Driver* (starting on page 32), we wanted to check how it handled various loads to test the robustness and versatility of the design. To do that, we came up with this design, and it was so handy that we have turned it into a standalone project.

Do note that this design is not infinitely adjustable and is not intended to sink a constant current. Instead, it uses switched resistance elements that apply discrete load resistance steps.

But being connected to an Arduino microcontroller means that it's possible to add some smarts. The circuit also includes components to allow the applied voltage and sunk current to be measured. This means that it can also calculate the power dissipated in the *Programmable Load* ($P = V \times I$).

Thus, you can program the *Load* to behave differently depending on the application. Its functions include fixed-resistance or current-tracking modes. It can even be programmed to provide a dynamic load so that you are able to test equipment under changing conditions.

A typical test for a power supply or regulator is to see how it responds to sudden changes in load resistance, and it is capable of doing that.

Our sample code provides just the basic features, including manual resistance and current-tracking modes, but it's easy to modify the code to add custom features. Our sample code also displays all the data that is collected.

Circuit details

Some variable load designs use a MOSFET bolted to a large heatsink as the load element. That requires some careful circuit design so that the *Load* can respond to dynamic conditions.

On the other hand, our *Programmable Load* consists of 15 high-power resistors which have no trouble dealing with rapidly changing conditions. Crucially, there is no chance of them presenting a short circuit as long as the circuit is operated within its working voltage range.

The concept is simple. There are four groups of 5W 47Ω power resistors. The groups consist of one, two, four and eight resistors respectively, which can be switched into any combination from none to 15 resistors in parallel.

The *Load* is optimised for use with voltage sources up to 12V nominal. But we've kept in mind that there can be some variation in voltage; for example, a 12V battery could put out up to 14.4V during charging, and a 12V LED might require 13V or more to produce full power. So we've selected components that will handle up to 15V continuously (more on a pulsed or intermittent basis).

47Ω is the lowest E24 series resistor value that produces less than 5W of dissipation with 15V applied across it, hence our use of 47Ω resistors.

Fig.1 shows the circuit we came up with. Four N-channel MOSFETs, Q1-Q4, switch the resistors in and out of circuit. Their sources are connected to circuit ground, and their drains go to the groups of one, two, four or eight resistors, respectively.

Features and Specifications

- **Handles up to 70W continuous, at up to 15V and 4.7A**
- **Presents a load resistance between 3.1Ω and 47Ω in 15 steps, or 43kΩ when 'off'**
- **Sinks 255mA to 3.83A in 255mA steps from a perfectly-regulated 12V source**
- **Manual control of unit loads or resistance**
- **Software provides an approximately constant-current mode**
- **Measures voltage up to 20V**
- **Measures current up to 6.5A**
- **Calculates power up to 130W**

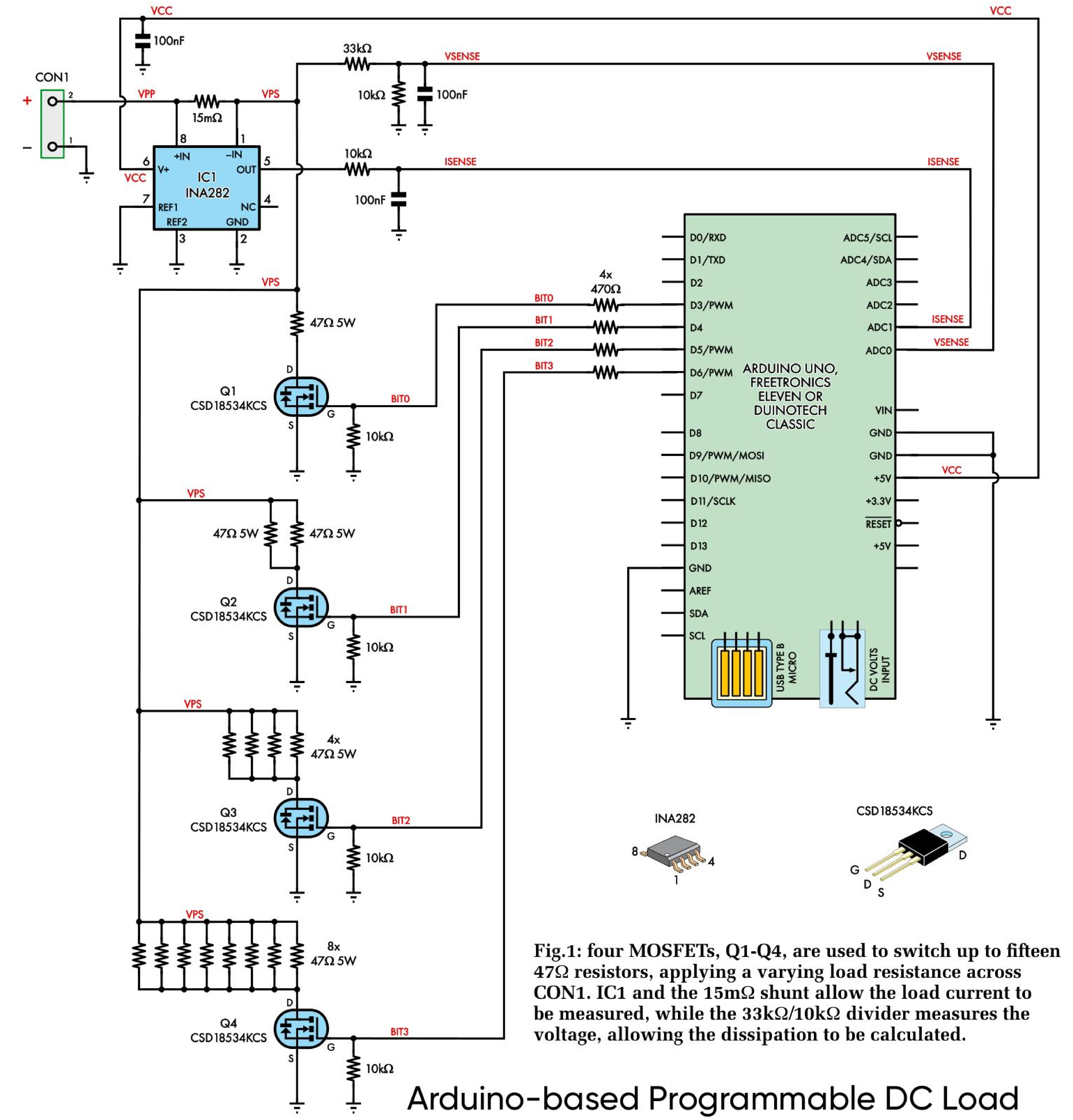

VCC
100nF
CON1
+
–
2
1
VPP
15mΩ
VPS
33kΩ
VSENSE
10kΩ
100nF
8
1
+IN
–IN
6
V+
IC1
INA282
OUT
5
VCC
7
REF1
NC
4
REF2
GND
3
2
10kΩ
ISENSE
100nF
VPS
47Ω 5W
D
Q1
CSD18534KCS
S
G
BIT0
10kΩ
4x
470Ω
BIT0
BIT1
BIT2
BIT3
D0/RXD
D1/TXD
D2
D3/PWM
D4
D5/PWM
D6/PWM
D7
D8
D9/PWM/MOSI
D10/PWM/MISO
D11/SCLK
D12
D13
GND
AREF
SDA
SCL
ARDUINO UNO, FREETRONICS ELEVEN OR DUINOTECH CLASSIC
ADC5/SCL
ADC4/SDA
ADC3
ADC2
ADC1
ADC0
VIN
GND
GND
+5V
+3.3V
RESET
+5V
ISENSE
VSENSE
VCC
USB TYPE B MICRO
DC VOLTS INPUT
VPS
47Ω 5W
47Ω 5W
Q2
CSD18534KCS
BIT1
10kΩ
VPS
4x
47Ω 5W
Q3
CSD18534KCS
BIT2
10kΩ
VPS
8x
47Ω 5W
Q4
CSD18534KCS
BIT3
10kΩ
INA282
8
4
1
CSD18534KCS
G
D
S
D

Fig.1: four MOSFETs, Q1-Q4, are used to switch up to fifteen 47Ω resistors, applying a varying load resistance across CON1. IC1 and the 15mΩ shunt allow the load current to be measured, while the 33kΩ/10kΩ divider measures the voltage, allowing the dissipation to be calculated.

Their gates are held low by 10kΩ resistors, so usually they are off.

The gates also connect to four digital I/O pins (D3, D4, D5 and D6) of an attached Arduino board via 470Ω resistors. The resistors provide a degree of protection in the event of a catastrophic failure. Otherwise, the circuits are entirely separate, apart from their common grounds.

The other end of the load resistors connects to a 15mΩ current-measuring shunt and then to the *Load's* positive terminal. The connection to the external circuitry is via screw terminals (CON1).

Also connected to the top of the load resistors is a 33kΩ/10kΩ divider with a 100nF capacitor across the lower resistor. This allows the attached Arduino board to measure up to 21.5V, assuming it has a 5V analogue-to-digital converter (ADC) reference voltage.

The divided and smoothed voltage is fed to the attached Arduino board's A0 analogue input pin. This divider means that the *Arduino Programmable Load* always presents a minimum load of 43kΩ.

The voltage across the shunt is measured by IC1, an INA282 current shunt monitor with a gain of 50. A current of 1A results in a 15mV drop across the 15mΩ shunt resistor, and thus an output of 750mV at IC1's pin 5. The maximum measurable current with a 5V reference is therefore 6.67A.

This voltage goes to another ADC channel at the Arduino A1 pin via a 10kΩ resistor, and it is filtered by a 100nF capacitor. The output voltage of IC1 is set to be referred to circuit ground by its pins 3 and 7 being connected to ground.

IC1 is fed with a 5V supply to its pin 6 with a 100nF bypass capacitor from the attached Arduino board, and its power ground connection is at pin 2.

By changing which of Arduino pins D3-D6 are high or low, the load presented can be varied between the value of 1-15 parallel 47Ω resistances, or even disconnected completely. The Arduino monitors the voltage and current and reports them along with calculated power dissipation.

Depending on its programmed mode, the *Load* can provide a fixed resistance or attempt to emulate constant current, or even a changing load to check the response of the supply.

Arduino board selection

We've specified an Arduino Uno in the parts list, but any 5V Arduino board, including other AVR-based R3 shield-compatible boards like the Leonardo or Mega, should work fine. The sample code doesn't use any pin-specific peripherals, so it isn't tied to a particular board. But 5V digital I/O levels are necessary to ensure that the MOSFETs turn on fully.

If you really want to use a 3.3V board, you could do so with some changes, but note that many are not compatible with the R3 shield form factor (they typically use the MKR form factor instead). One exception is the Due. We have not tested the design with a 3.3V Arduino board, but we believe it will work with the following changes:

- Ensure you use the IPP80N06S4L-07 (or similar MOSFETs) because the CSD18534KCS are not suitable for 3.3V gate drive.
- change the 33kΩ resistor to 56kΩ and change the 15mΩ shunt to 10mΩ. This is to avoid overloading the ADC pins with voltages above 3.3V and assumes a default ADC reference of 3.3V (as per the Due).
- In the sketch, change the V_CONST define to 0.0212695 and the I_CONST define to 0.0064453 to account for the different component values.

Construction

The *Load* is presented as a bare shield PCB with external screw terminals. It's expected to be used similarly to the *Arduino PSU* (February 2022), as a bare board on top of an Arduino-compatible microcontroller board.

The lack of enclosure actually helps us somewhat. With up to 70W of dissipation, a good amount of free air convection is necessary to avoid overheating. Ideally, a fan should be pointed at the module when it is used at or approaching its maximum power rating.

The *Load* is built on a double-sided PCB coded 04105221, which measures 89 x 54mm and is available from the PE PCB Service. Fig.2 shows where all the components go.

Start by fitting the small components. IC1 is an SMD part in an SOIC-8 package and is best soldered with the aid of flux paste and tweezers, although you might get away without them.

Apply flux to the pads and tack one lead in place with a clean iron tip, ensuring pin 1 is aligned with the dot on the PCB. If the part is still correctly aligned, solder the remaining pins; otherwise, adjust it using tweezers until you can do so. The 15mΩ shunt resistor adjacent to CON1 can also be handled similarly, although it is not as fiddly to mount.

Clean up any excess flux at this point as the remaining parts are all through-hole. Note that the PCB will also accept a through-hole resistor for the shunt if that suits you better. Remember that you will have to tweak the calibration in the software if you change its value.

Next, fit the remaining small axial resistors, as marked on the PCB silkscreen. Check the resistors with a multimeter if you are unsure of their values.

Follow with the three 100nF capacitors, all of which are near IC1. These are not polarised. Trim all leads close on the underside of the PCB. Screw terminal CON1 can be soldered next. Ensure that the lead entries face out of the board.

The next tallest components are MOSFETs Q1-Q4, all of which are the same type. Make sure to orient them correctly, with the tabs aligning to the silkscreen markings. You can also refer to the photos and Fig.2 to confirm the mounting arrangement for these MOSFETs.

The MOSFETs are mounted free-standing and vertically. They do not drop much voltage when on and do not handle much current relative to their ratings, so they do not need heatsinking.

Prepare the 5W ceramic resistors by bending one lead 180° down one side so that they can be slotted vertically onto the PCB. Bending the lead down the side opposite the markings gives the neatest result (see photo below).

When fitting the 5W resistors, it will also help to stand them slightly above the PCB to allow more room for air to circulate; again, you can see this in our photos. We've made a 3mm gap, although the length of their leads might limit you in this.

Start with the resistors near the centre of the PCB and work outwards, trying to keep the tops level for uniformity and square up the parts within their pads. Note that some parts are not on the 'grid' to provide clearance from the DC socket and USB socket.

Trim the leads neatly and flush against the rear of the PCB.

The only remaining parts are the pin headers. First, plug them into the Arduino board so that they are correctly aligned, then slot the shield on top.

Before soldering them, check for any conflicts below. The in-circuit serial programming (ICSP) headers on the Uno board are exposed high points and are the most likely to foul any pins on the *Load* PCB that are not trimmed short enough. Also ensure that the PCB is down firmly against the pin headers, then solder them together from above.

Programming it

Our fundamental control sketch (program) for the *Load* is controlled through the Arduino Serial Monitor for simplicity. The voltage, current and power are also reported this way. Screen 1 shows a typical display on the Arduino Serial Monitor during use.

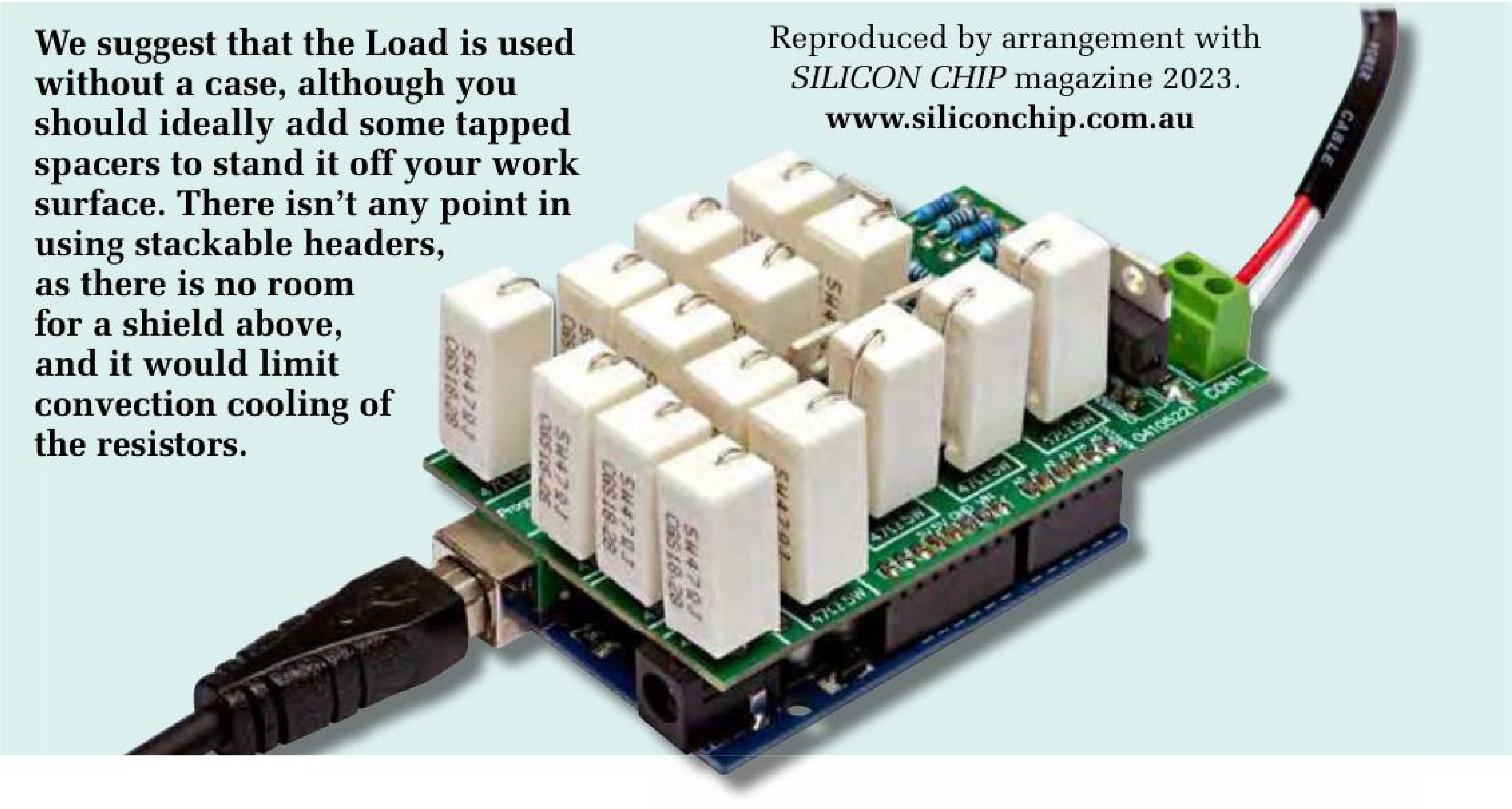
If you don't have the Arduino IDE (integrated development environment), start by downloading it from **https://bit.ly/pe-jun23-ide** and then install it.

Now open the sketch file (download from the June 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**) and select your board (eg Uno, Leonardo or Mega) and serial port from the Tools menu. Upload the sketch and then open the Serial Monitor from the Tools menu. Set the baud rate to 115200.

You should start to see an output similar to Screen 1, with updates occurring several times per second. Note that the measured voltage is across the *Load* itself, so the power shown is what is being dissipated in the *Load*.

Testing and usage

A good way to test the *Load* is to connect a multimeter to CON1 to measure



We suggest that the Load is used without a case, although you should ideally add some tapped spacers to stand it off your work surface. There isn't any point in using stackable headers, as there is no room for a shield above, and it would limit convection cooling of the resistors.

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the resistance between its terminals. The positive multimeter lead should connect to the '+' terminal and the negative to '–'. Note that if a reverse current is applied, it will be conducted by the MOSFET body diodes (and thus all the resistors) and will appear as a 3Ω load.

There are three modes that our software can operate in. The first is manual mode, selected by typing the letter 'm' into the Serial Monitor, followed by a number from 0 to 15. This is simply the number of resistors that will be paralleled and presented as the load.

So for '1', Q1 is switched on, while '2' means that Q2 is on, '3' results in both Q1 and Q2 being on, and so on. This continues up to '15', when all the MOSFETs are switched on.

For example, typing 'm1' and pressing Enter (ensuring the 'CR' line ending is selected) will cause a 47Ω load to be presented on CON1. Entering 'm2' will choose a 23.5Ω load. You can check these with your multimeter, although you might see slightly higher values than expected due to lead resistance.

The 'm0' command will disconnect all resistors – a good one to remember if something goes wrong.

The second mode is where a resistance is entered using the 'r' command. The software finds the nearest possible resistance value to the entered value. Of course, there are only 15 discrete steps, so it will hardly ever be exact. But it is a good way to approximate resistive loads of a known value.

The emulated constant-current mode is started with the 'i' command, and it attempts to match the measured current to the setpoint by ramping up and down the number of unit loads.

With the limited number of steps, it too can only approximate the set current, and will not respond to rapidly changing conditions. In practically all cases, it will jump between two adjacent load levels, and the current will zigzag around the setpoint. Screen 1 shows this, with the *Load* switching between 3 and 4 resistors to maintain a current near 70mA. This was set using the 'i0.07' command.

If the voltage rises above 15V or the power goes over 70W for an extended period, shut the *Load* down with the 'm0' command to avoid damage to the resistors. There should not be any damage to the MOSFETs as long as the voltage stays below the MOSFETs' rated drain-source voltage, which is 60V for the recommended types.

Remember that the displayed voltage cannot go above 21.5V, so it might be much higher than shown if it is above 20V.

More usage tips

Connect the Arduino Programmable Load's negative terminal to your circuit ground (remember that it is also commoned with the computer controlling it) and the '+' terminal to a positive output.

For example, a power supply should be connected '+' to '+' and '–' to '–'. If other loads need to be inserted in series, they should be connected between the PSU '+' and *Load* '+' to ensure that the *Load* '–' stays at ground potential.

Parts List – Arduino Programmable Load

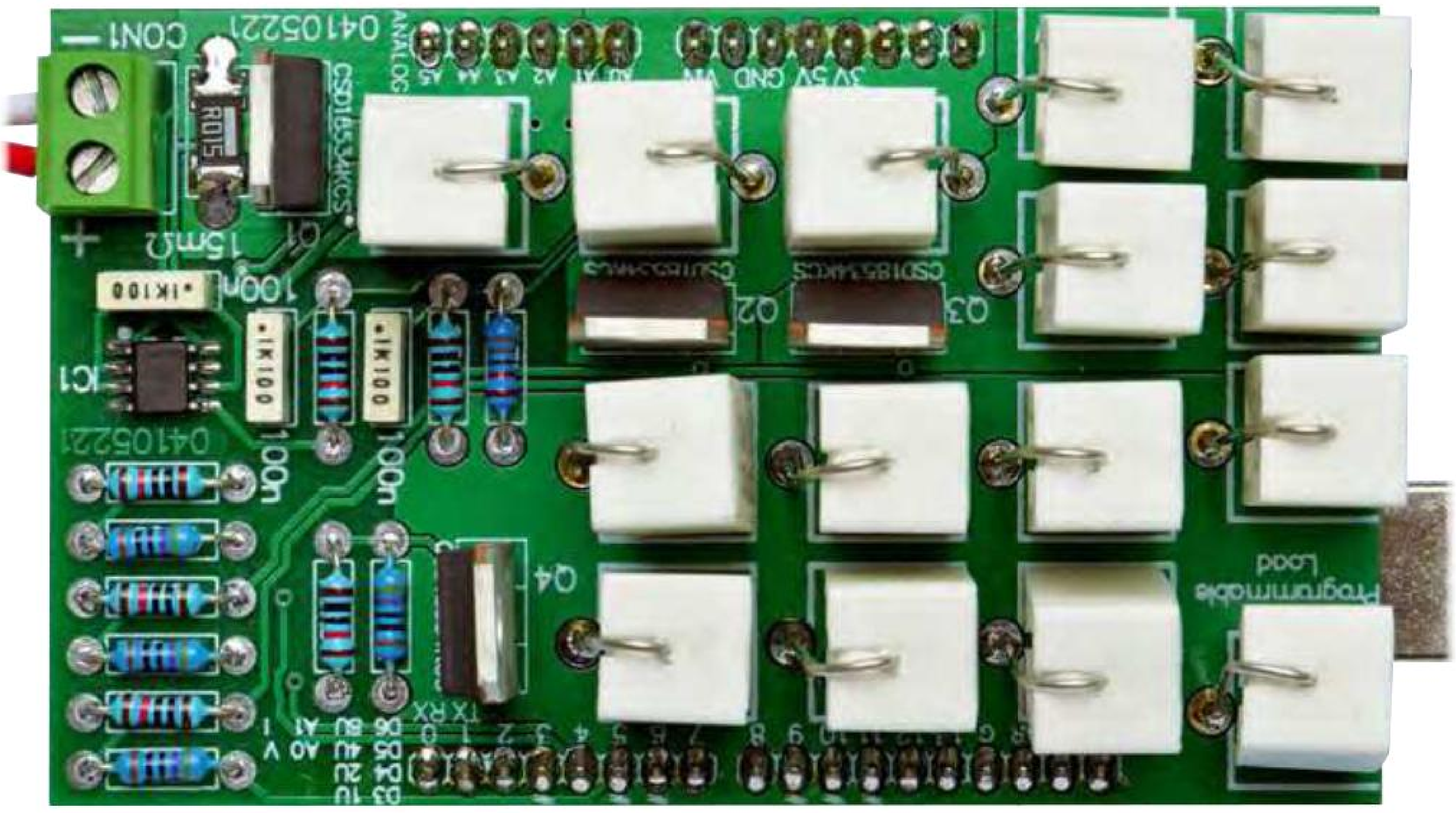
1 double-sided PCB coded 04105221, 89 x 54mm, available from the *PE PCB Service*
1 5V Arduino-compatible board (eg, Uno, Leonardo or Mega)
1 10-way 2.54mm-pitch pin header
2 8-way 2.54mm-pitch pin headers
1 6-way 2.54mm-pitch pin header
1 2-way 5/5.08mm pitch screw terminal block (CON1)

Semiconductors
1 INA282 current-shunt monitor, SOIC-8 (IC1)
4 CSD18534KCS, IPP80N06S4L-07 or similar N-channel logic-level MOSFETs, TO-220 (Q1-Q4) **[2 x Cat SC4177 or 4 x Cat SC6184]**

Capacitors
3 100nF MKT capacitors

Resistors *(all 1% ¼W axial unless otherwise stated)*
1 33kΩ
6 10kΩ
4 470Ω
1 15mΩ 1-3W M6332/2512-size SMD **[Cat SC3943]**
15 47Ω 5W 10% wirewound

Q1-Q4 could be just about any logic-level (ie, suitable for 5V drive) N-channel MOSFETs in TO-220 packages with sufficient voltage and current ratings.



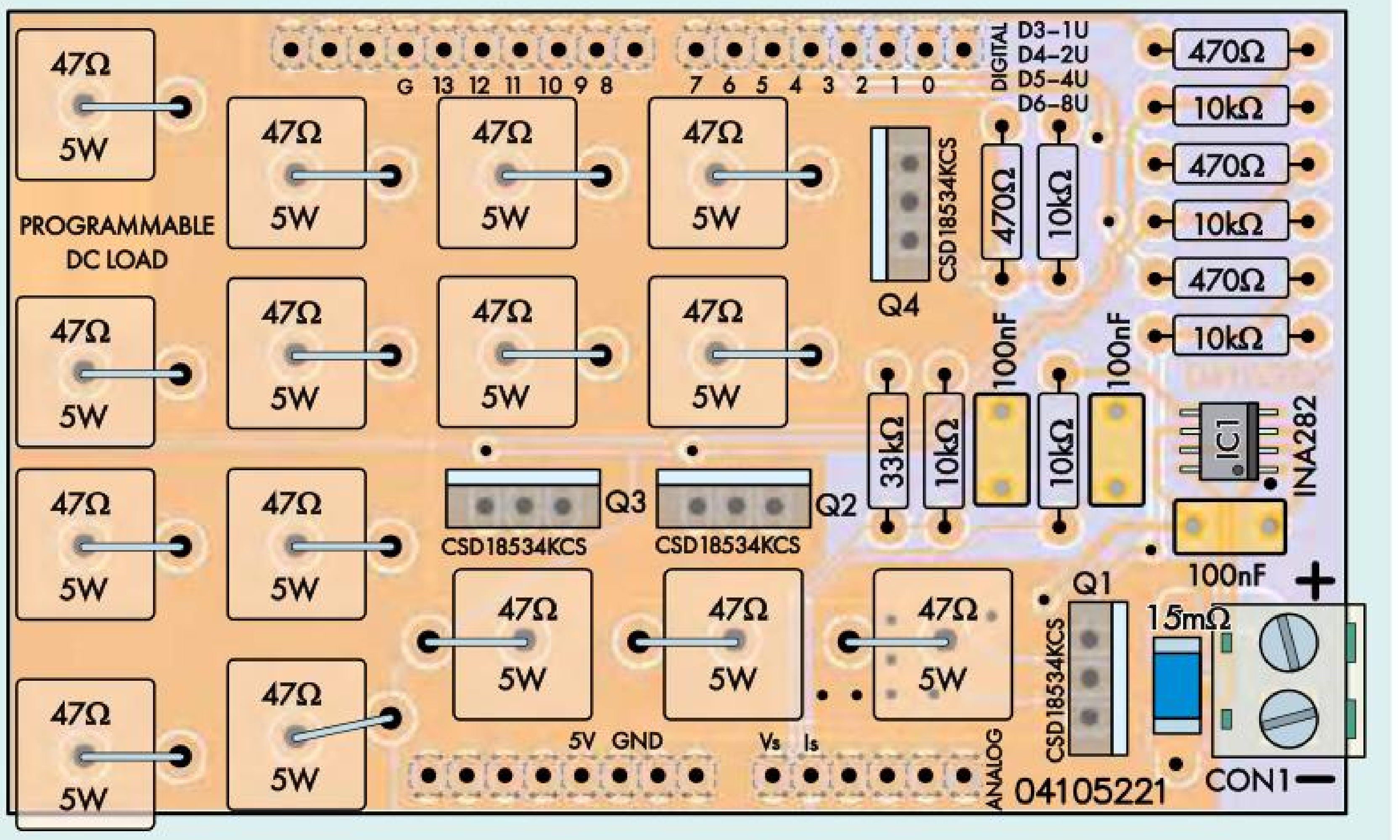
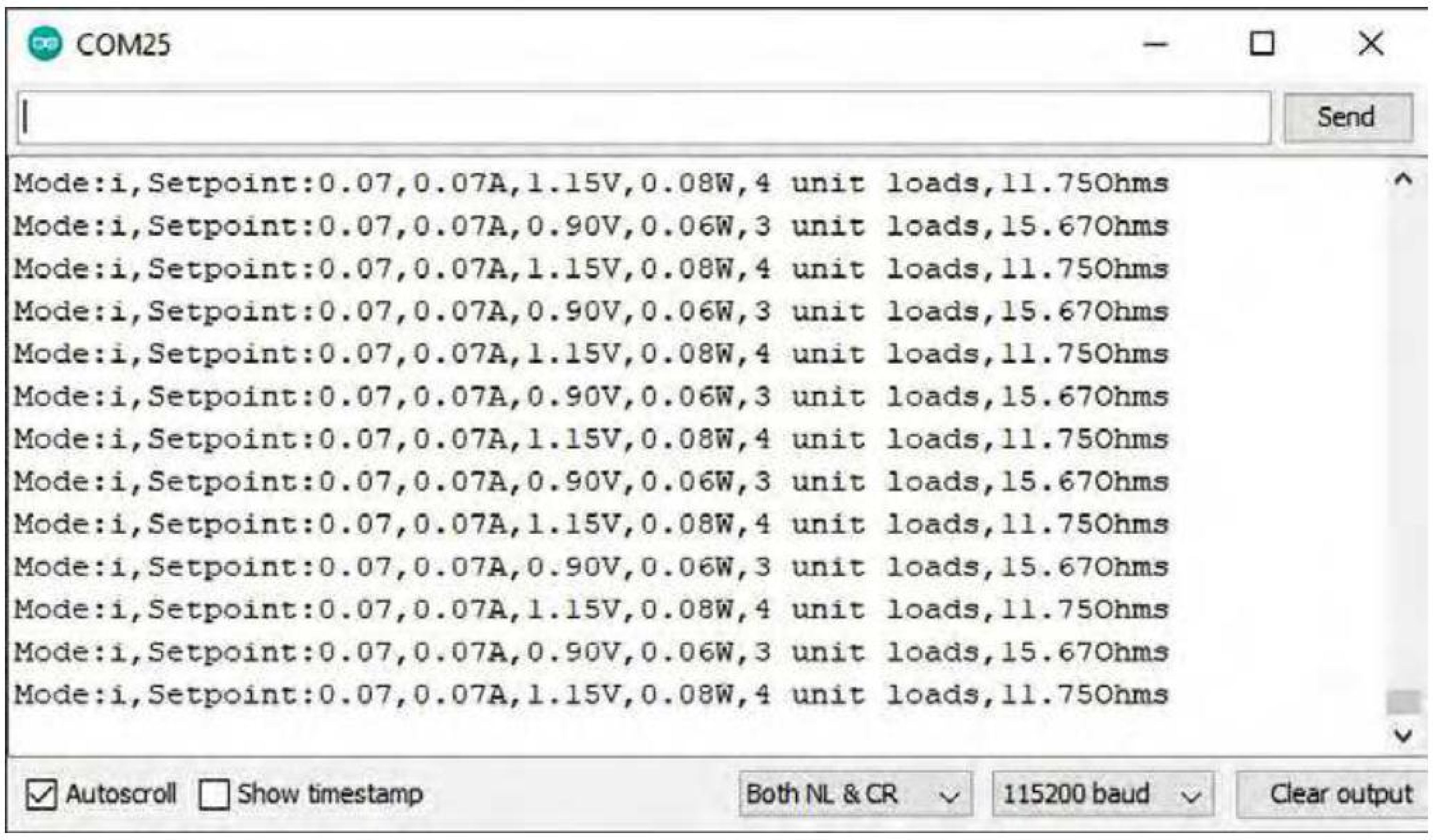


Fig.2: the board is easy to assemble, but it's best to take some care to line up the 5W resistors neatly or it will look messy. Watch out for the orientation of the MOSFETs and IC1. Also, check the underside of the PCB when it is fitted to the Arduino board to ensure that none of the shield component leads short against anything on the Arduino. The 15mΩ shunt can be fitted as an SMD or through-hole resistor.

The *Load* is well suited to testing solar panels, with the proviso that the MOSFET drain-source voltage is respected, especially under open-circuit conditions when panels produce their highest voltages. This limits it primarily to solar panels with a nominal 24V output; these can produce up to 44V under open-circuit conditions.

A manual scan of the sixteen different load levels will create sixteen data points that can be plotted on an I/V or P/V curve. But note that we are also designing a Solar Panel Tester which will have more features than the *Load* can offer, so stay tuned for that in the near future.



```
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
Mode:i,Setpoint:0.07,0.07A,0.90V,0.06W,3 unit loads,15.67Ohms
Mode:i,Setpoint:0.07,0.07A,1.15V,0.08W,4 unit loads,11.75Ohms
```

Screen 1: the Serial Monitor (or other serial terminal program of your choice) is used to control the unit and show its status. It has current, voltage and power read-outs, and the applied load is displayed in ohms and the number of 47Ω units. In the 'constant current' mode used here, the load resistance is controlled to keep the current near a setpoint.

Making modifications

The software is written with most parameters set by #define statements near the start.

If you wish to modify the load resistors, all must remain the same resistance (unless you make significant changes to the software). The unit load resistance is specified by the R_CONST value.

A higher test voltage might require a different divider to change the range (although you will need to check that the MOSFETs can also handle a higher voltage). A different divider will mean that the V_CONST multiplier will need to change.

To calculate the new value for V_CONST, work out what applied voltage will deliver 5V to the A0 pin of the Arduino, then divide that higher voltage by 1024. The default value of 0.0209961 is simply 21.5V divided by 1024.

We have used (as much as possible) PWM-capable pins so that it is possible to emulate intermediate resistance values by applying PWM signals to the MOSFETs. We have not tried this technique, but you could experiment with it if you need finer resistance controls than the discrete steps presented here.

Note that this will present a pulsed load to the current/voltage source, and depending on what it is, it might react in an unexpected manner.

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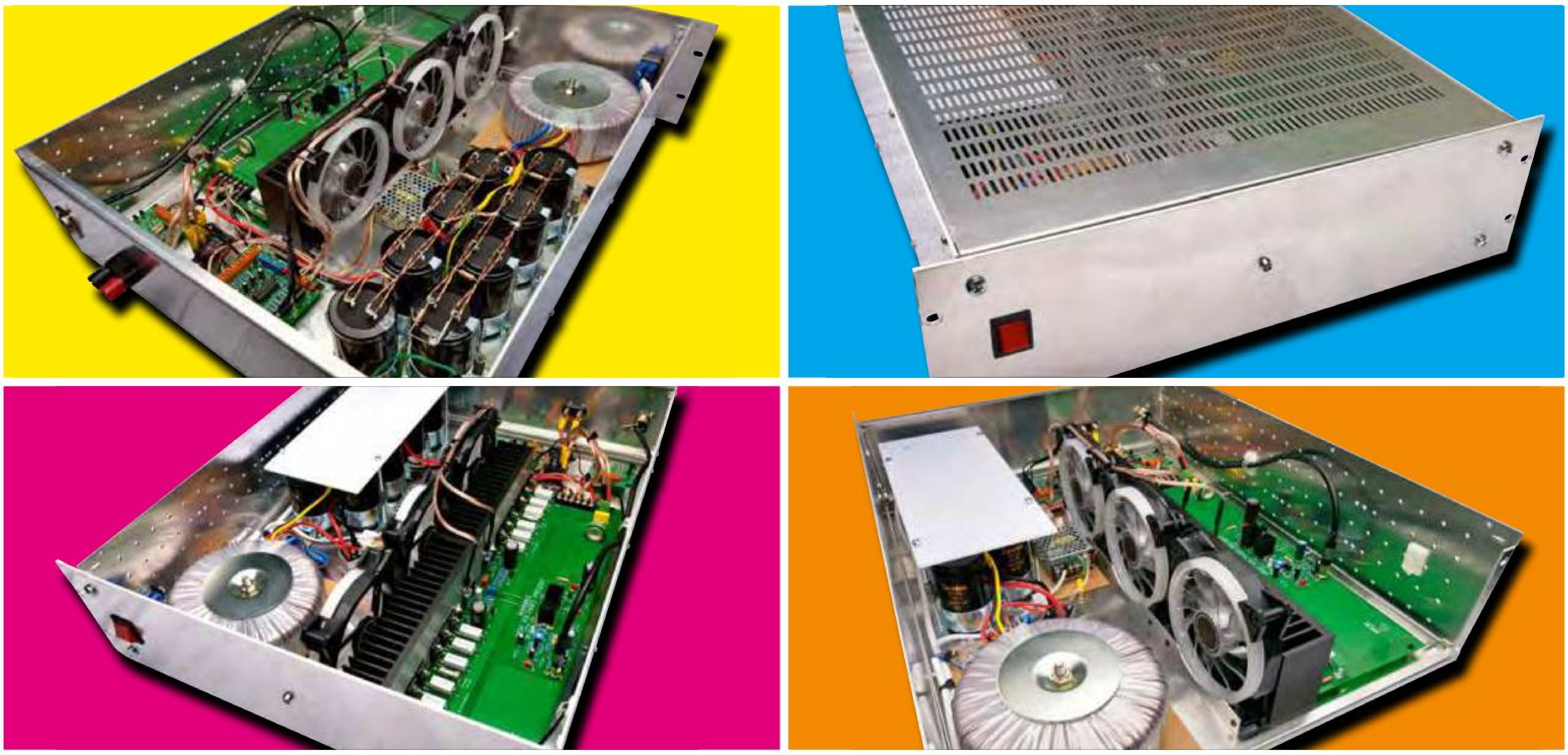
500 WATTS POWER AMPLIFIER

PART 3

BY JOHN CLARKE



To finish our new 500W Amplifier, we shall now describe the power supply configuration and the complete assembly details. That includes mounting all the modules and parts in the enclosure, wiring it up, checking that it works and making the calibration adjustments.

The 500W Amplifier module we've described over the last two issues cannot operate alone. It needs a power supply and added circuitry to protect the loudspeaker and keep it cool.

We are using two additional projects for these tasks: the *Amplifier Clipping Indicator* (April 2023) and the *Fan Controller & Loudspeaker Protector* (February 2023).

The final circuitry to be described is the *Amplifier's* power supply, and its circuit is shown in Fig.9. As you would expect for this *Amplifier*, the power supply uses a large transformer, rated at 800VA.

The transformer has two independent 115V primary windings and two independent 55V secondary windings. The two 115V windings are connected in series so it can be powered from the (nominally) 230V AC mains. Similarly, the two 55V windings are connected in series with a centre tap so that after rectification and filtering, we get approximately ±80V DC.

Considerable capacitance is used to filter the DC supply, with four 10,000uF 100V capacitors filtering the positive supply and another four for the negative supply. This is to remove much of the ripple from the DC supply rails, especially when under load, as the *Amplifier* can draw many amps when delivering the peak power it is capable of achieving.

Three 15kΩ 1W resistors are connected in parallel from both supply rails to ground to discharge the capacitors when the amp is switched off. LEDs are included in series with one resistor on each side of the supply, as voltage presence indicators.

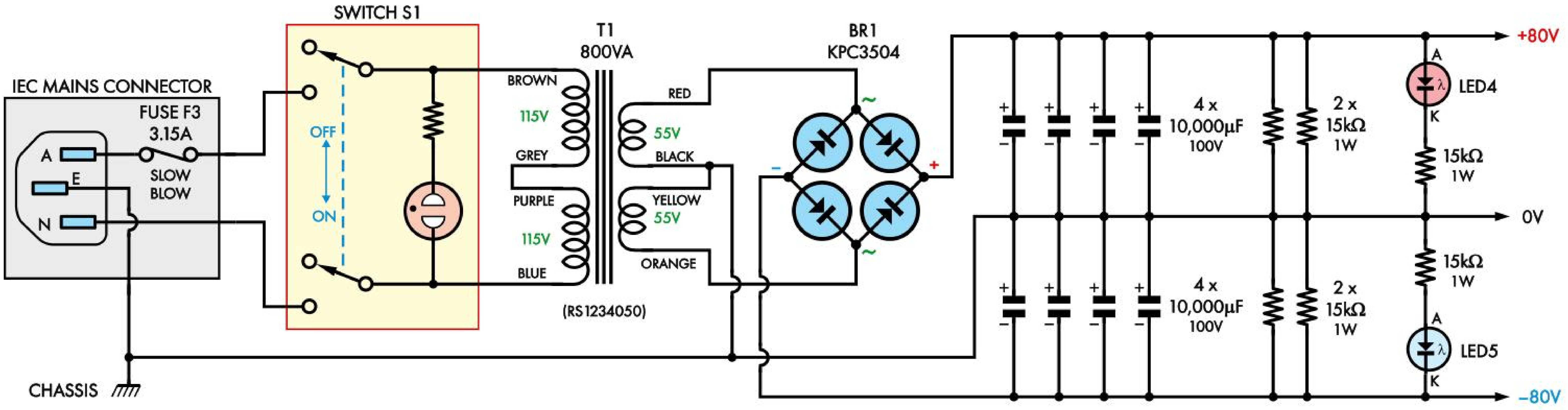
They ensure that the capacitors do not remain charged to high voltages for too long after the power is switched off. This is for safety reasons since the total of around 160V DC is an electrocution risk. Additionally, a plastic cover over the capacitors (removed in some photos for clarity) prevents accidental contact with the high-voltage wiring and capacitor terminals.

The bridge rectifier is rated at 35A 400V. This rating is sufficient to handle the initial surge current that charges

Danger: High Voltage

The 160V DC supply across the filter capacitor bank and the amplifier supply rails is potentially lethal!

After the power supply wiring is complete and before you apply power, mount a clear perspex sheet over the capacitor bank to protect against inadvertent contact – now or in the future! Note and remember that the capacitors take some time to discharge after the power is switched off.



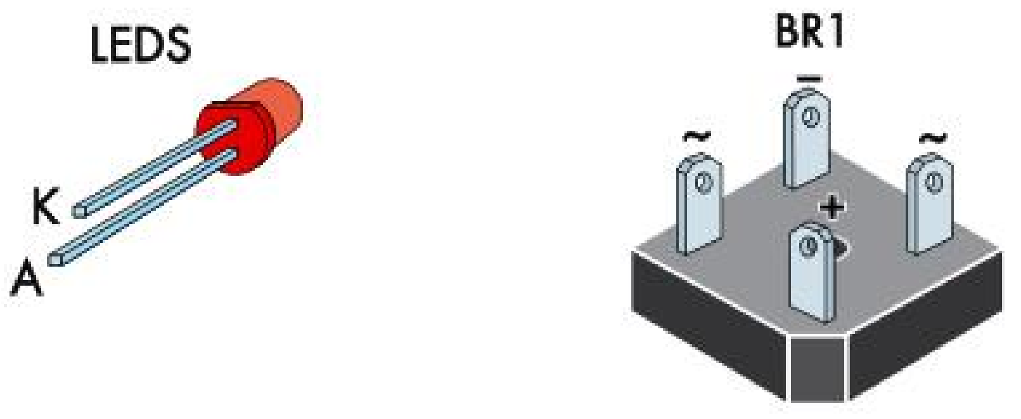


Fig.9: the only remarkable aspect of the power supply circuit is the large 800VA transformer and relatively high ±80V supply rails. Several 15kΩ discharge resistors are needed due to the high total capacitance.

the capacitors at power-up, and the repetitive capacitor charging current peaks that occur near the peak of the rectified waveform for each mains half-cycle.

The transformer is a toroidal type, and a slow-blow fuse is required to prevent it from blowing when power is initially applied, as the inrush current can be very high. For this transformer, a 3.15A M205 slow-blow fuse is specified. It is installed within the IEC power connector housing. This has a safety fuse enclosure, where the fuse cannot be accessed until the IEC power lead is unplugged.

The power supply is installed and wired up within a 3U rack case that houses the *Amplifier Module*, heatsink fans, the *Amplifier Clipping Detector*, *Loudspeaker Protector & Fan Speed Controller* and other necessary components.

Enclosure layout

The internal layout for the *Amplifier* and associated parts is shown in Fig.10. The *Amplifier* is built into a 3U rack case with a solid baseplate and vented top lid. This layout allows the amplifier heatsink to be mounted inside the enclosure with three cooling fans that draw air in from one side of the lid and pass this air across the heatsink fins. That forces airflow upwards, to remove heat from the heatsink.

The fans are taller than the heatsink, so any air coming up past the fins is blown sideways and then out through the vented lid on the other side.

There are quite a few holes that need to be drilled for all the mounting hardware, various cutouts made for the power switch, XLR and IEC sockets, the loudspeaker terminals and clipping indicator LED. The locations for these are shown in Fig.10, and the close-up detail drawings in Fig.11-Fig.13.

Begin with the front and rear panels. Some of the required cutouts are not circular; you can cut these by drilling a series of small holes around the inside of the required perimeter, knocking out the piece of metal and filing to shape.

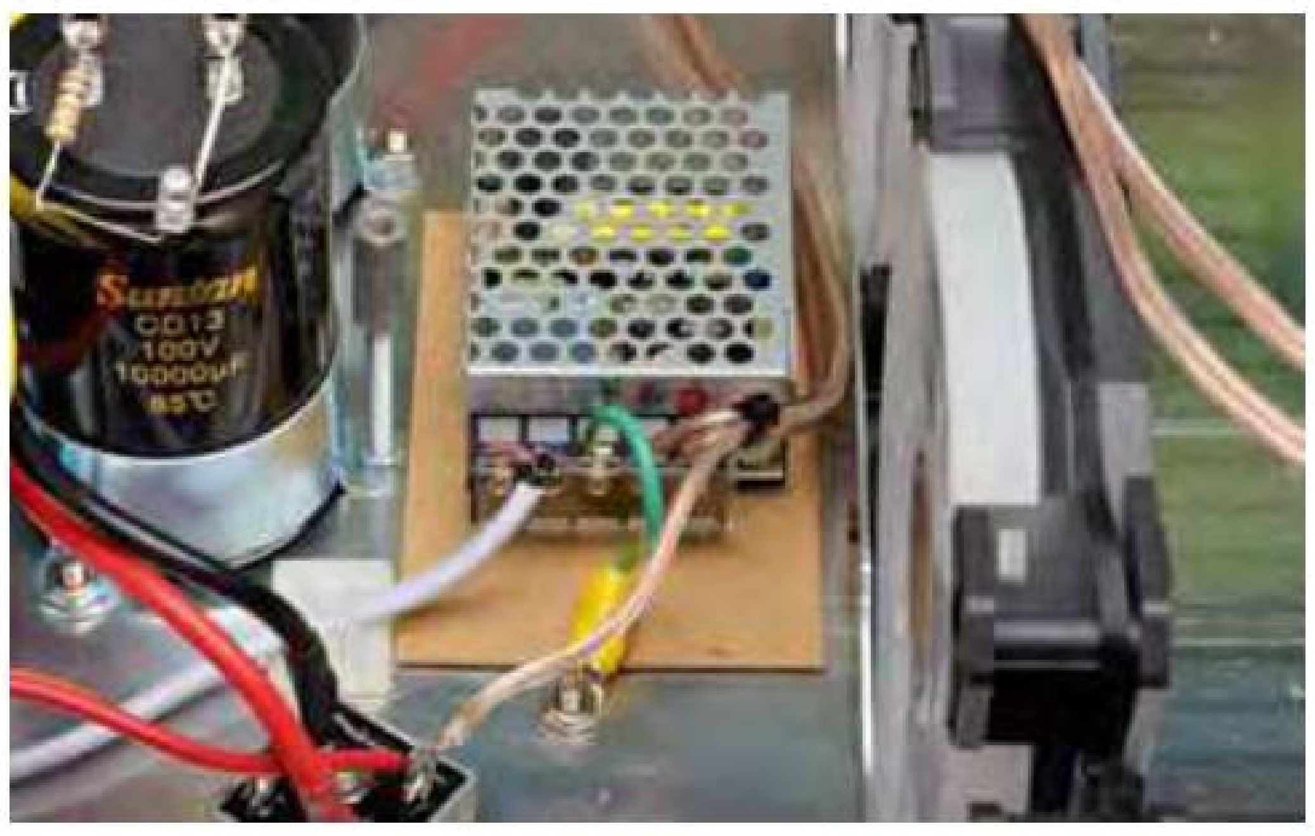
Note that you could dispense with the XLR input socket and just use an insulated panel-mount single RCA socket. This depends on your intended application; XLR would be better suited for PA use, while RCA might be fine for home use. If using an RCA socket, a single-core shielded cable is all that's needed to connect internally to the *Amplifier Module* input.

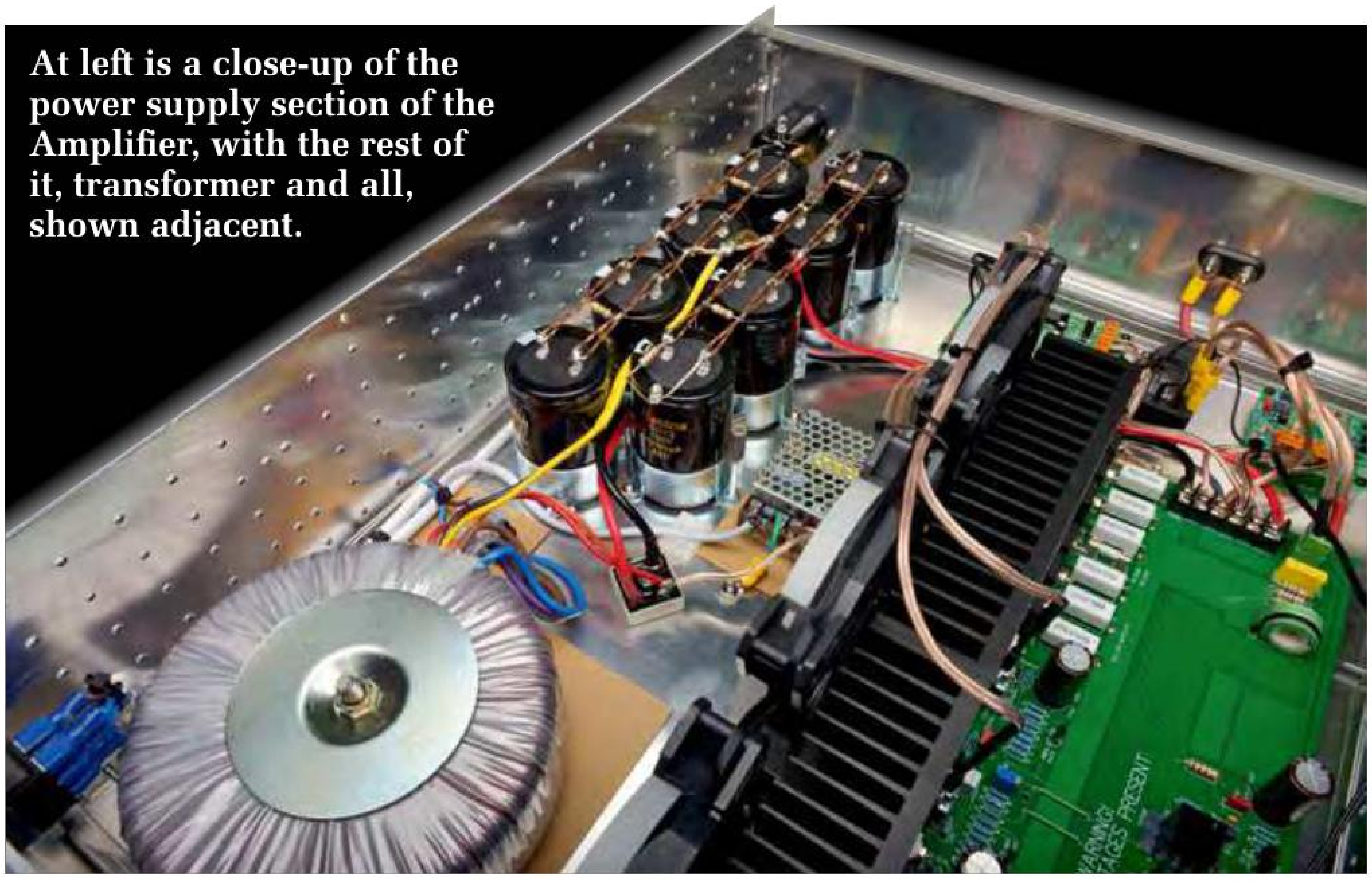
We specify an insulated RCA socket because the connections need to be isolated from the chassis. Otherwise, a hum loop will be caused by earthing the signal ground to the chassis in two places, since it is already earthed by the *Amplifier Module*.

If using the XLR socket, the main XLR cutout can be made using a 22mm Speedbor drill and then filing the hole shape. Now make holes in the front panel for the power switch and clipping indicator LED bezel similarly. You can make a copy of the front panel label (Fig.14) and use that as a template for positioning those two holes.

Next, prepare the insulating material sections to go under the transformer, the 3-way mains terminal strip and the 12V switchmode supply. The insulation for the transformer prevents voltage flash-over to the earthed chassis should there be an insulation breakdown. The other insulators prevent a live wire from contacting the chassis if it disconnects from its terminal.

Cut the required insulation pieces from the 208 x 225mm sheet with scissors or a sharp knife and ruler. The sizes





At left is a close-up of the power supply section of the Amplifier, with the rest of it, transformer and all, shown adjacent.

Note that inductor L1 is wound using 13.5 turns of 1.25mm diameter wire, not 30.5 turns or 1mm diameter as explained in last month's PE.

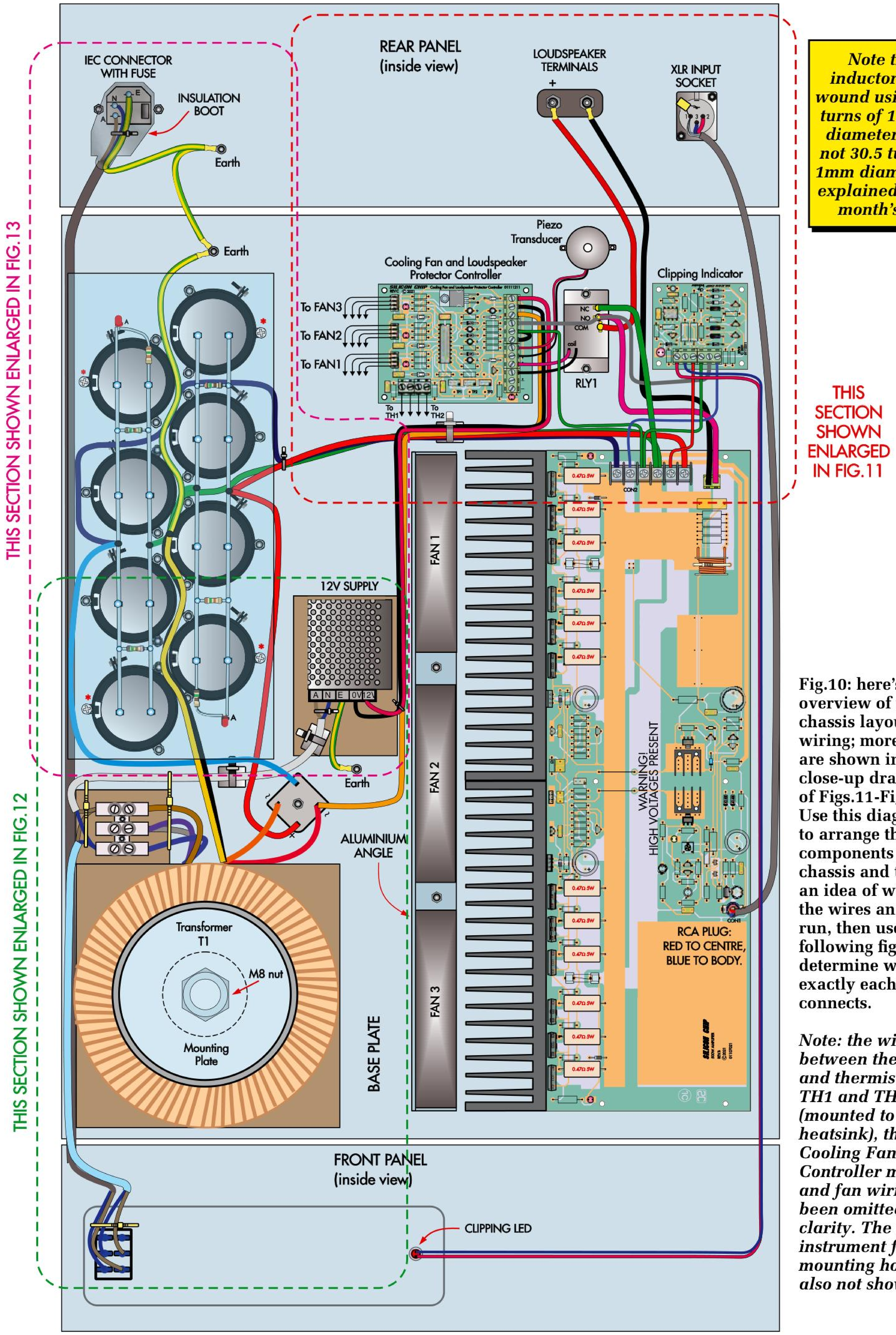
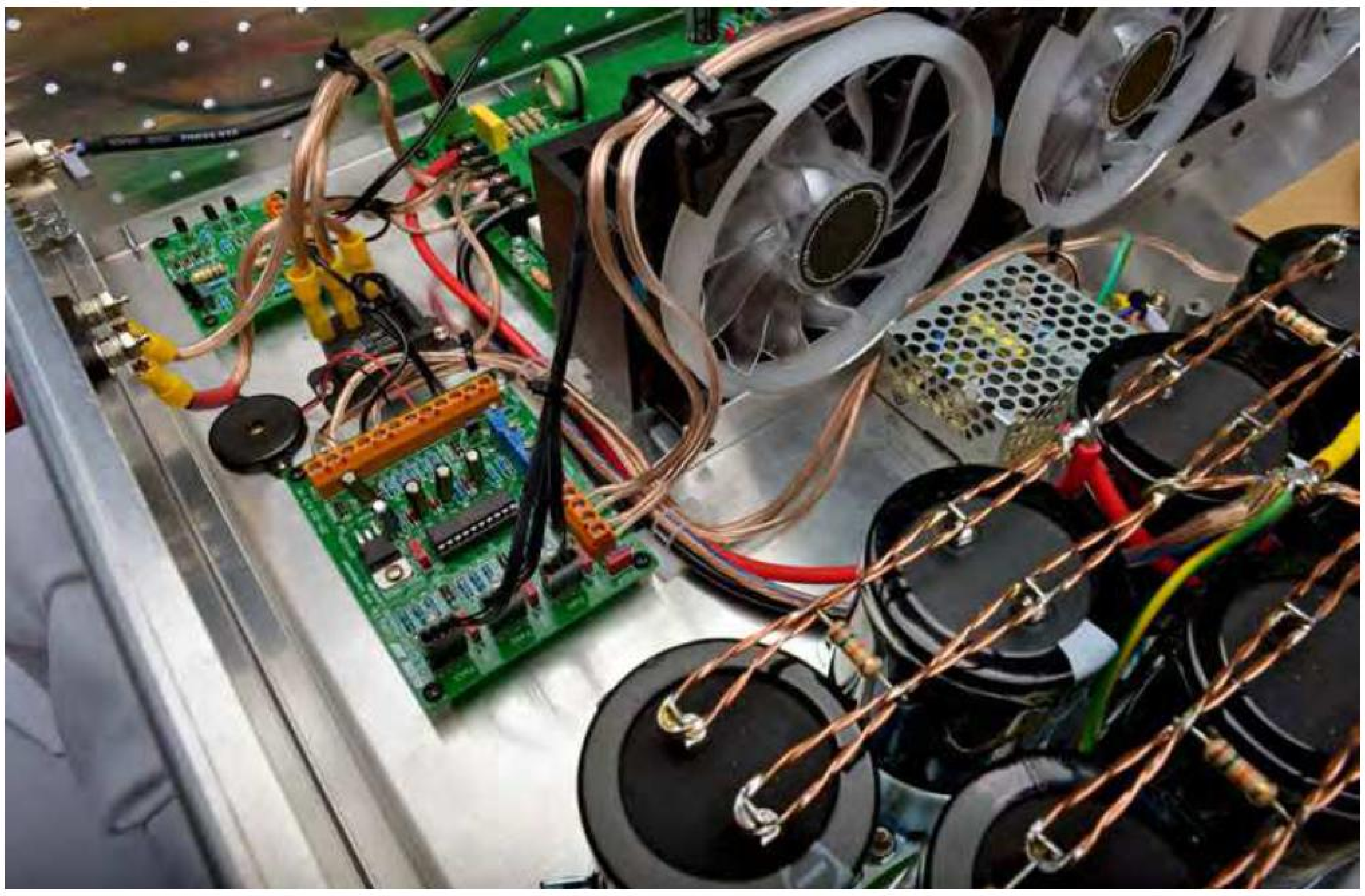

REAR PANEL (inside view)
IEC CONNECTOR WITH FUSE
N
E
A
INSULATION BOOT
Earth
Earth
LOUDSPEAKER TERMINALS
+
XLR INPUT SOCKET
1
3
2
Piezo Transducer
Cooling Fan and Loudspeaker Protector Controller
To FAN3
To FAN2
To FAN1
To TH1
To TH2
NC
NO
COM
coil
RLY1
Clipping Indicator
THIS SECTION SHOWN ENLARGED IN FIG.11
THIS SECTION SHOWN ENLARGED IN FIG.13
THIS SECTION SHOWN ENLARGED IN FIG.12
12V SUPPLY
A N E 0V 12V
Earth
CON2
0.47Ω 5W
FAN 1
FAN 2
FAN 3
WARNING! HIGH VOLTAGES PRESENT
CON1
RCA PLUG: RED TO CENTRE, BLUE TO BODY.
ALUMINIUM ANGLE
Transformer T1
M8 nut
Mounting Plate
BASE PLATE
FRONT PANEL (inside view)
CLIPPING LED

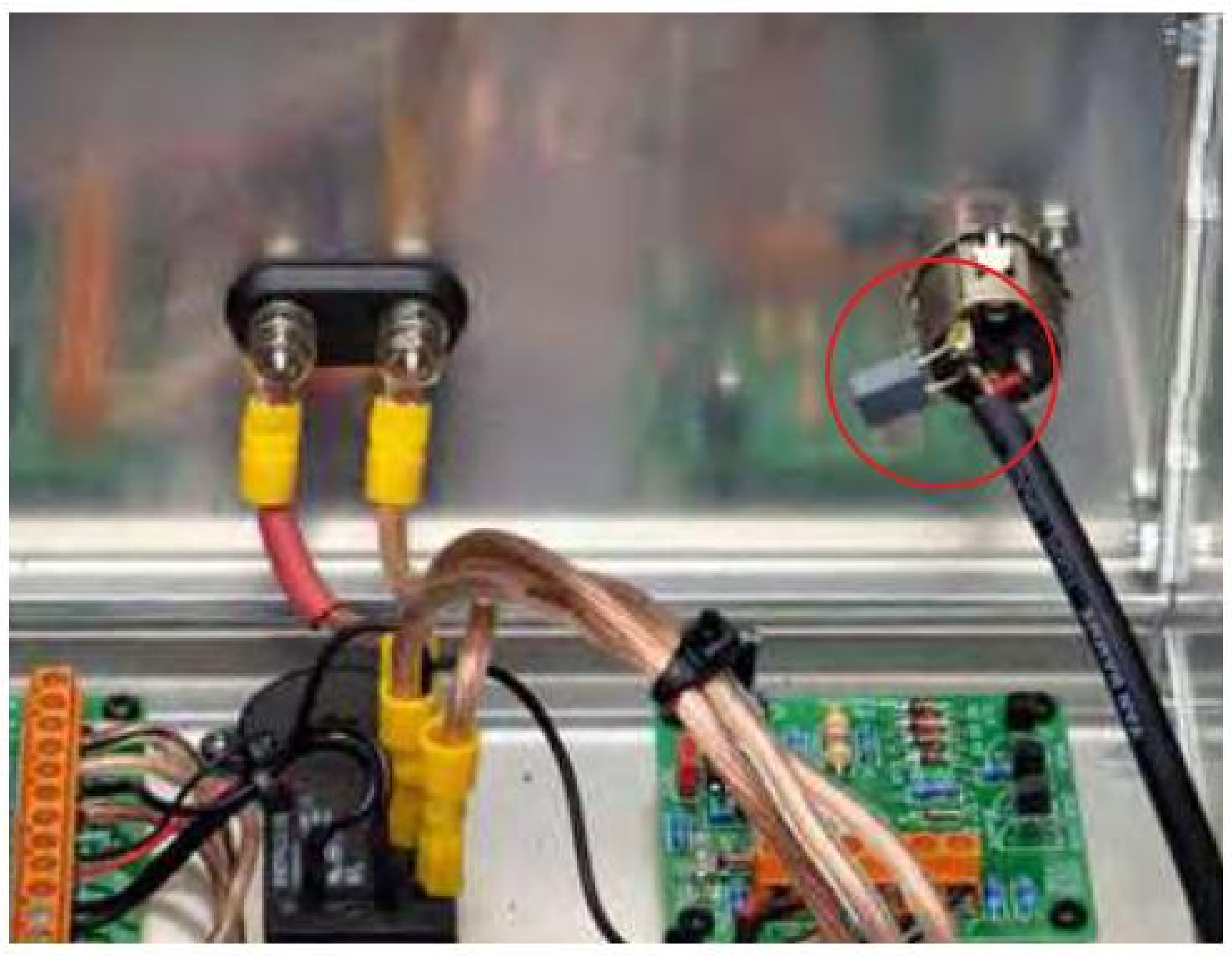
Fig.10: here's an overview of the chassis layout and wiring; more details are shown in the close-up drawings of Figs.11-Fig.13. Use this diagram to arrange the components in the chassis and to get an idea of where the wires and cables run, then use the following figures to determine where exactly each wire connects.

Note: the wiring between the fans and thermistors TH1 and TH2 (mounted to the heatsink), the Cooling Fan Controller module and fan wiring has been omitted for clarity. The corner instrument feet mounting holes are also not shown.

required are 63 x 97mm for the 12V supply, 57 x 45mm for the 3-way terminals and 162 x 162mm for the transformer.

An 8mm hole is needed in the centre of the transformer insulator. That can be made using a wad punch (giving a cleanly cut hole) or an 8mm drill, after which you can clean up the resulting furry edges with a hobby knife.





All of the various modules are attached to the case by mounting screws. The wiring between these modules is also cable tied to the case. It's a good idea to be generous with cable ties as it keeps everything secure and neat. Note that the XLR input socket has a 560nF capacitor soldered to it, as shown above.

3mm holes are also needed in the other insulation pieces for the mounting holes of the 3-way terminals and those on the underside of the 12V supply. Again, a small wad punch is ideal for making these holes. A 3mm drill can be used instead, although the resulting holes will not be clean.

Arranging the parts

At this point, it's a good idea to place all the major components in the chassis and make sure you're comfortable with all their positions. Mark them out with a fine felt-tip pen. That way, you can be sure everything is positioned correctly before you start making holes.

When initially laying out the parts in the baseplate, be sure to allow room for the equipment feet to be secured in the corners with M3 screws and nuts. In particular, check that the transformer can be positioned without the screw and nut for the equipment foot in that corner interfering.

The holes required in the aluminium baseplate include the mounts for the four corner equipment feet (3mm), the three PCBs (3mm), the heatsink (3mm), the relay (3mm) and piezo transducer (2.5mm), the earth lug holes (4mm), capacitor mounting holes (4mm), the 12V supply (3mm), the three-way mains terminals (3mm), the bridge rectifier (4mm) and transformer (8mm). Refer to Fig.10-Fig.13 to see the locations.

You'll also need to make holes to hold the aluminium right-angle bracket for mounting the fans near the heatsink (4mm). It's best to locate it after the heatsink has been mounted. The aluminium bracket itself will also need holes to attach the fans that are spaced evenly along the 400mm length, with one fan in the centre and the others at each end.

The angle piece is secured to the base by two 4mm screws in the gaps between the fans. We made a small semicircular cutout for each fan to prevent the lower portion of the bracket from covering the fan blade area. But that is not strictly necessary; it's just nice to have.

While there needn't be any particular order to install the parts within the case, it is easier to mount the lighter ones first. The transformer is the heaviest part, so attach it last. There is a list of the screws and nuts in Table 1 to help you select the correct hardware for each job.

Install the IEC socket, the speaker terminals and the XLR socket on the rear panel. Then mount the switch and clipping indicator LED bezel on the front panel. However, leave these panels detached from the enclosure until the rest of the wiring is complete.

Now is a good time to mount the thermistors for the *Cooling Fan Controller*. These are mounted against the amplifier heatsinks behind the Q25 and Q26 transistor clamp screws. The wires from the thermistors will need extending with an approximately

Table 1: Screw and nut usage

Equipment feet	four M3 x 10mm machine screws, four hex nuts
Amplifier PCB mounting	six M3 x 5mm machine screws, three 9mm M3-tapped nylon standoffs
Heatsink mounting	four M3 x 10mm machine screws
Speaker Protector PCB	eight M3 x 5mm machine screws, four 9mm M3-tapped standoffs
Clipping Indicator PCB	eight M3 x 5mm machine screws, four 9mm M3-tapped standoffs
12V switch-mode supply	two M3 x 6mm machine screws
Capacitor mounting	20 M4 x 10mm machine screws, 32 M4 hex nuts, eight M4 x 50mm machine screws, four M4-tapped joiners (for mounting protective cover)
3-way mains terminal block	two M3 x 15mm machine screws, two M3 hex nuts
Bridge rectifier	one M4 x 20mm machine screw, one M4 hex nut
Earth connections	three M4 x 15mm machine screws, three 4mm star washers, four M4 hex nuts, 3 5.3mm diameter crimp eyelets
Transformer mounting	one M8 x 75mm bolt, M8 washer, M8 hex nut
Aluminium angle mounting	two M4 x 10mm machine screws, two M4 hex nuts
Relay	two M3 x 10mm machine screws, two M3 hex nuts
IEC connector	two M3 x 12mm countersunk head machine screws, two M3 hex nuts
XLR connector	two M3 x 12mm countersunk head machine screws, two M3 hex nuts
Piezo transducer	two No.4 x 6mm self-tapping screws or two M2 x 6mm machine screws and two M2 hex nuts

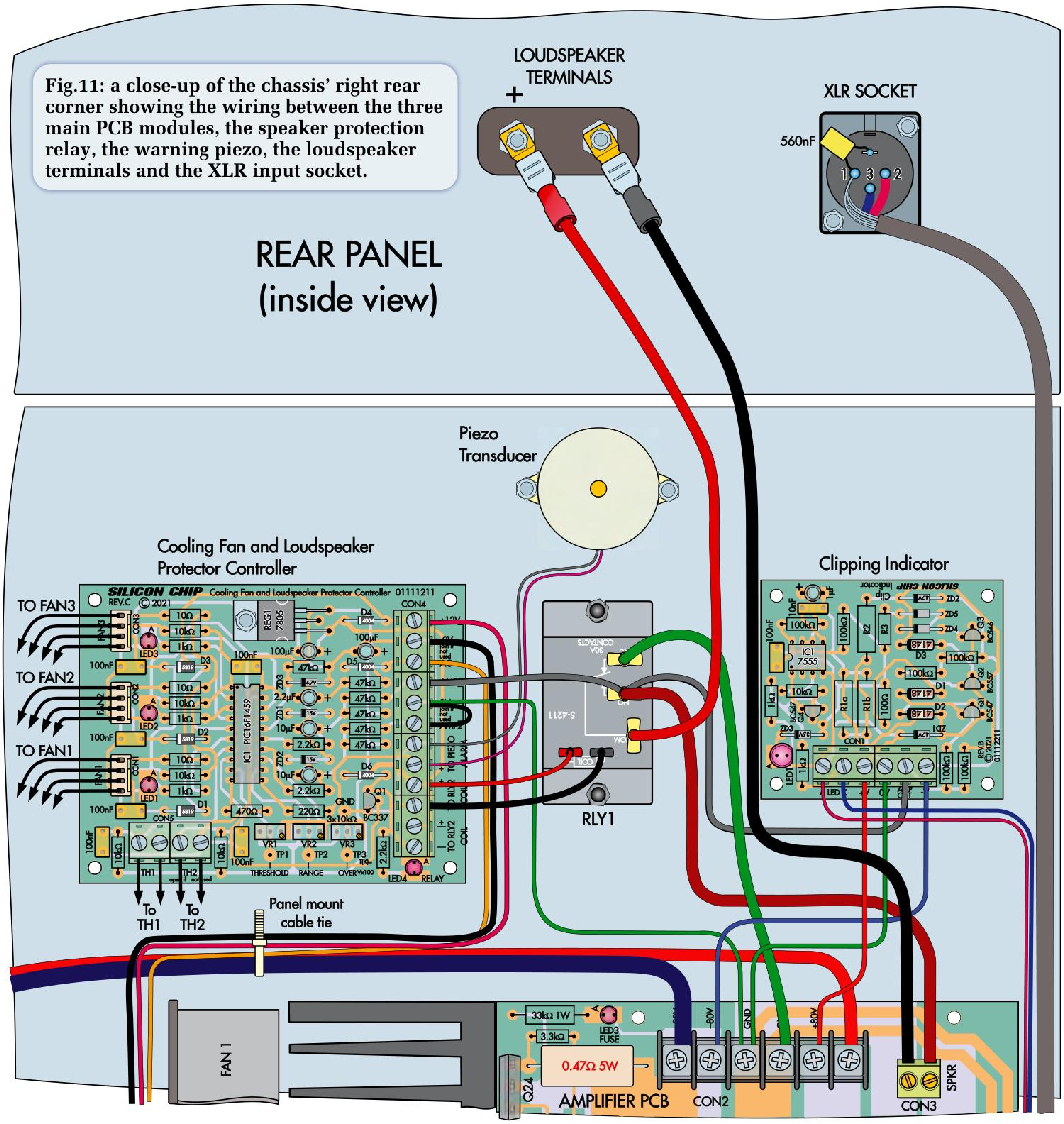


Fig.11: a close-up of the chassis' right rear corner showing the wiring between the three main PCB modules, the speaker protection relay, the warning piezo, the loudspeaker terminals and the XLR input socket.

LOUDSPEAKER TERMINALS
+
XLR SOCKET
560nF
1
3
2
REAR PANEL (inside view)
Piezo Transducer
Cooling Fan and Loudspeaker Protector Controller
SILICON CHIP Cooling Fan and Loudspeaker Protector Controller 01111211
REV.C © 2021
CON4
TO FAN3
TO FAN2
TO FAN1
IC1 PIC16F1459
REG1 7805
LED1
LED2
LED3
LED4
Q1
BC337
VR1
VR2
VR3
TP1
TP2
TP3
THRESHOLD
RANGE
OVER
RELAY
TO PIEZO
TO RLY2 COIL
To TH1
To TH2
Panel mount cable tie
RLY1
S-4211
30A CONTACTS
Clipping Indicator
SILICON CHIP Clip Indicator
IC1 7555
CON1
LED
FAN 1
33kΩ 1W
3.3kΩ
LED3 FUSE
0.47Ω 5W
Q24
AMPLIFIER PCB
CON2
-80V
GND
+80V
CON3
SPKR

350mm length of light-gauge figure-eight wire; insulate the joints with heatshrink tubing.

Next, mount the three PCBs in the chassis on 9mm nylon standoffs using M3 x 5mm screws. The *Amplifier Module's* primary mounting is via the screws into the heatsink. The *Amplifier Module* has three PCB mounting locations at the edge away from the heatsink that attach using spacers and short machine screws, but these should be installed last to avoid stressing the PCBs.

Before mounting the capacitors, cut out the capacitor plastic covering piece measuring 295 x 125mm, place this on the base plate and mark out the four 4mm mounting holes. These coincide with the capacitor mounting clamp screws marked with asterisks in Fig.10 and Fig.13.

Now mount the capacitors. These must be oriented with the correct polarity. The negative side is marked with a minus symbol down one side of the capacitor body. When oriented correctly, tighten down the clamps to prevent them from rotating.

Note that the four capacitor bracket mounting locations marked with asterisks are secured using 50mm-long screws and nuts. Once all the capacitors are mounted, place M4 joiners on the end of these four 50mm screws, ready to attach the capacitor covering piece using four more M4 x 50mm screws.

Now mount the 12V switchmode supply with the insulation board beneath it, and the three-way mains terminal block, also with the insulation underneath.

Next, attach the fans to the aluminium bracket using the supplied securing screws, then mount the bracket and fan assembly to the baseplate.

To improve heat transfer, when attaching the bridge rectifier to the base, smear a little heatsink compound on the mating surface and the chassis.

Transformer mounting

Place a washer onto the M8 bolt for the transformer and insert it from the underside of the baseplate. Place the insulation square onto the baseplate over the screw, then add a neoprene washer on top of this, followed by the transformer, the second neoprene washer, the mounting disc and then the M8 nut. Orient

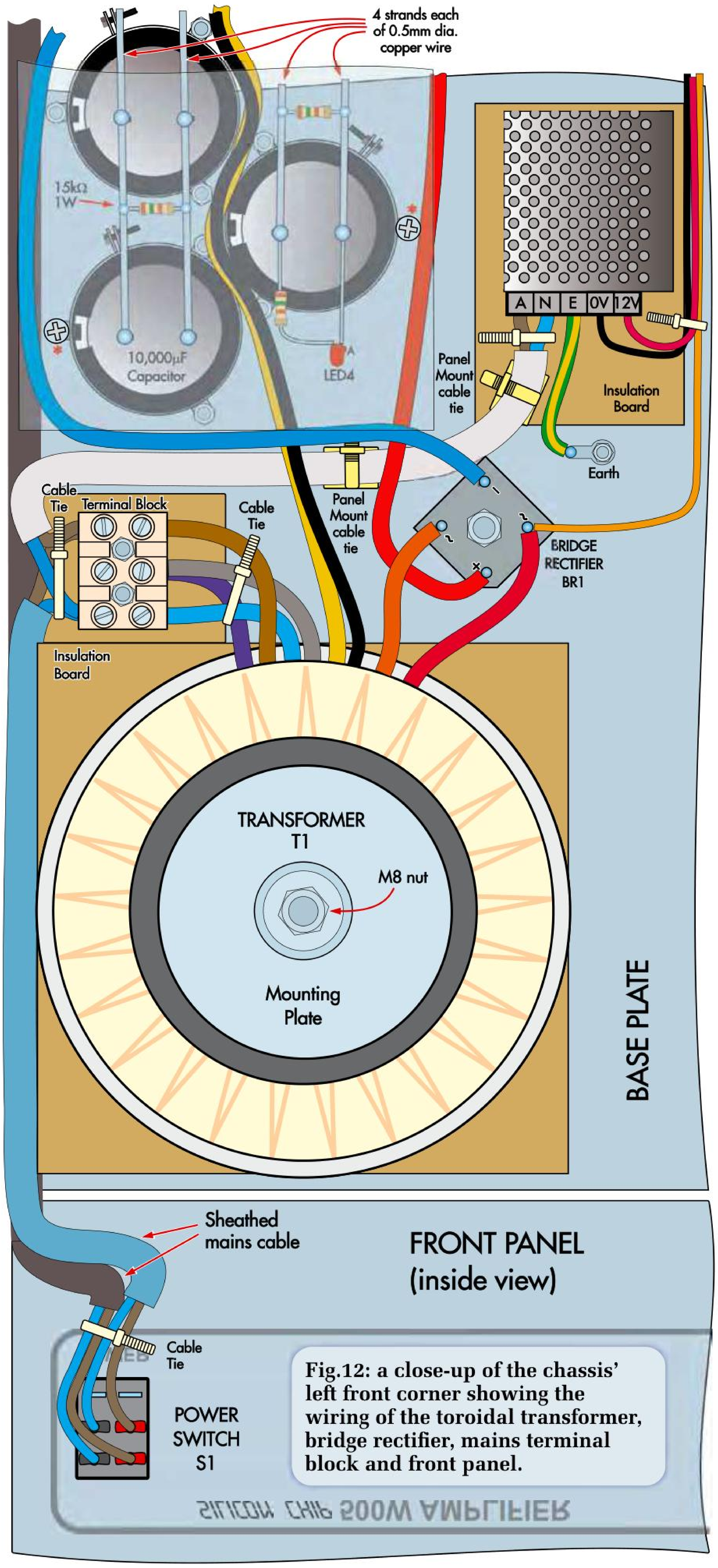

4 strands each of 0.5mm dia. copper wire
15kΩ 1W
10,000µF Capacitor
LED4
A
Panel Mount cable tie
A N E 0V 12V
Insulation Board
Earth
BRIDGE RECTIFIER BR1
Cable Tie
Terminal Block
Cable Tie
Panel Mount cable tie
Insulation Board
TRANSFORMER T1
M8 nut
Mounting Plate
BASE PLATE
Sheathed mains cable
FRONT PANEL (inside view)
Cable Tie
POWER SWITCH S1
SILICON CHIP 500W AMPLIFIER

Fig.12: a close-up of the chassis' left front corner showing the wiring of the toroidal transformer, bridge rectifier, mains terminal block and front panel.

the transformer as shown in Fig.10 and Fig.12 and tighten the nut.

Wiring it up

Most of the remaining work involves the heavy-duty power supply wiring.

Wire the two banks of four capacitors in parallel using strands of 0.5mm-diameter copper wire. We twisted two strands together using a drill and then bent this in half, interweaving the wire around the capacitor terminals, as shown in the photos. Solder the wires securely to the terminals.

Both sides of the filter capacitor bank have two 15kΩ 1W bleed resistors connected across them. Also, a red LED is connected across each side of the capacitor bank in series with another two 15kΩ resistors. The LEDs are positioned to protrude through 5mm holes in the capacitor cover plate. If your cover plate is made from clear or translucent plastic, you could skip making those holes.

These LEDs indicate when voltage is present across the capacitors. As you will find, even with these bleed resistors, it takes quite a while for the capacitors to discharge after the *Amplifier* is switched off.

The whole *Amplifier* uses single-point earthing, so it is important to follow the wiring details in Fig.10-Fig.13 closely.

Mains wiring

The mains supply is via the IEC power socket, then a length of twin-core mains flex rated at 7.5A or more. This wire needs to pass through the IEC insulation boot before being terminated (soldered) to the IEC socket terminals.

The earth wire also passes through the insulation boot and is secured to the earth terminal on the IEC socket, and to the chassis using a crimp eyelet secured with an M4 screw, star washer and nut. Note that this earth continues to also connect to the baseplate via another eyelet.

Tie the mains wires with a cable tie before placing the insulating boot cover over the rear of the IEC socket. A third eyelet and earth wire connects from the baseplate earth point to the star earth between the capacitor banks.

The mains wires from the IEC socket connect to the power switch using crimp spade connectors on the top two terminals. It is important to wire this switch the right way around; otherwise, the neon LED will be lit, regardless of whether the *Amplifier* is on or off.

We placed unused insulated crimp spade connectors on the lower two switch terminals just for safety. The mains wires from the power switch at the centre terminals run to an insulated three-way terminal block. Further mains wiring connects to the 12V switchmode supply. The mains wires must all be cable tied together so that if one comes loose, it will not cause a safety issue by shorting to chassis.

Note that the 12V supply also has an Earth connection to the chassis using an eyelet secured to the baseplate with an M4 screw, star washer and nut.

Transformer wiring

We've shown the transformer wiring using the colour coding of the recommended transformer. But check on the transformer label that your winding colours are the same as we used; if not, wire it up according to the colours for your transformer.

Connect the two 115V primary windings in series by joining the purple and grey wires using the centre terminal of the 3-way terminal block.

Run the wiring to the filter capacitors from the bridge rectifier using the 2.9mm^2 (cross-sectional area) wire with red for positive and black for negative. You will find that the yellow and black transformer wires are not long enough to reach the star earth point, so extend them using one of the 2.93mm^2 figure-8 cables.

The power supply wiring is basically complete at this stage, but it is not connected to the *Amplifier Module*. Check for continuity between the chassis and the earth connection on the IEC connector. You should get a reading very close to 0Ω. Next, install the 3.15A slow-blow fuse into the IEC socket.

Check your work to ensure everything is connected correctly. Be sure that the capacitors are all oriented correctly. Check that the positive terminal on the bridge rectifier connects to the positive side of the capacitor bank, and that the negative terminal of the bridge rectifier connects to the negative side of the capacitor bank.

Safety precautions

After the power supply wiring is complete and before you apply power, we suggest that you mount the cover sheet over the bank of capacitors. This will prevent accidental contact with the 160V DC supply. The total DC supply is potentially lethal.

The cover will also provide a degree of safety if one of the capacitors overheats and vents to the atmosphere.

Before powering it up for the first time, wear safety glasses or a face shield. Briefly apply power and check that both LEDs light. Then switch off the power and allow the capacitors to discharge completely. It should take a while for the LEDs to stop glowing, and they should go out at around the same time.

If all is OK, remove the capacitor safety shield and, taking great care (as the capacitor voltages are dangerous), switch on power again and measure the capacitor voltages. The readings you get should be close to ±80V DC. Check also that the 12V supply provides 12V DC at its output terminals. Switch off the power, and again, wait for the voltage to drop to near zero.

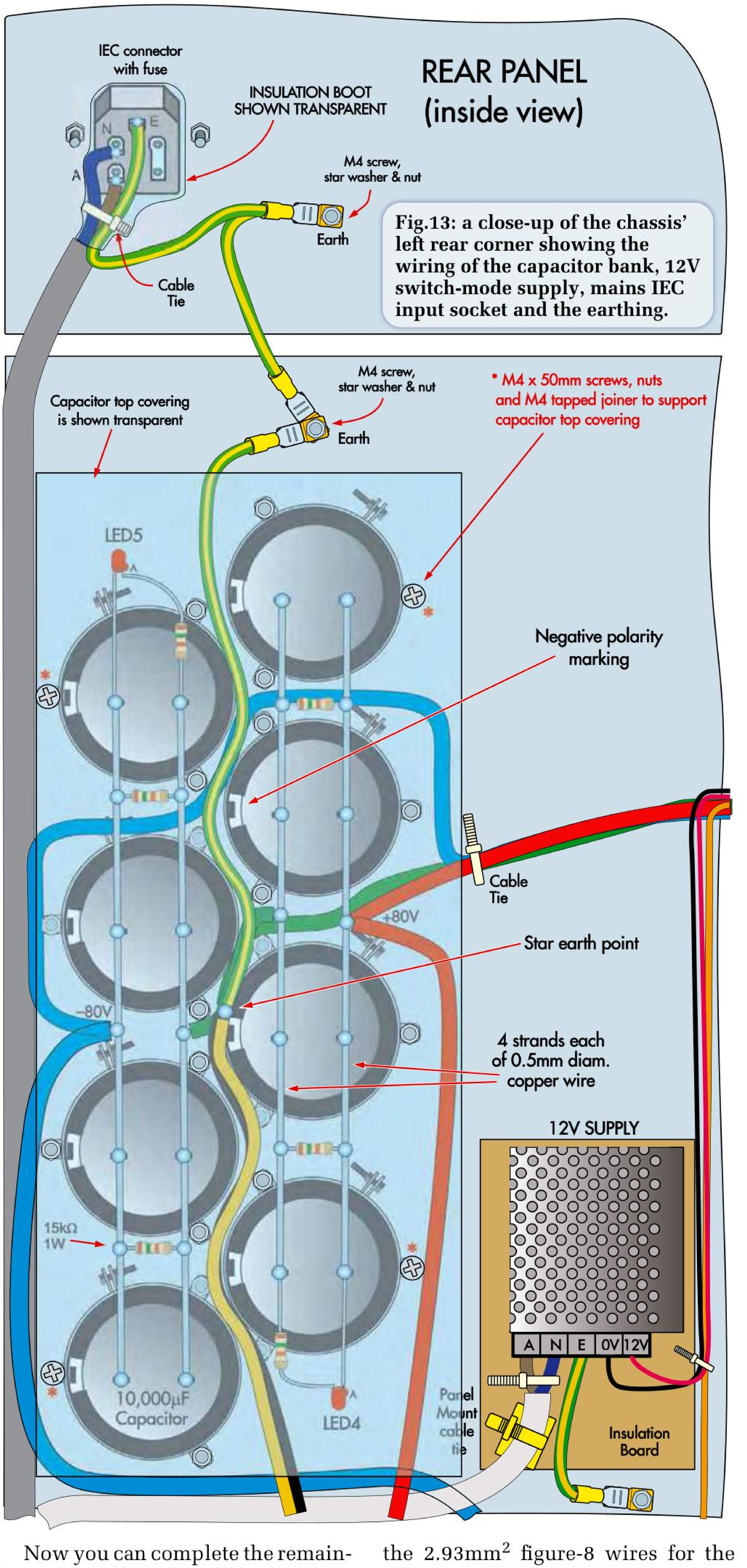
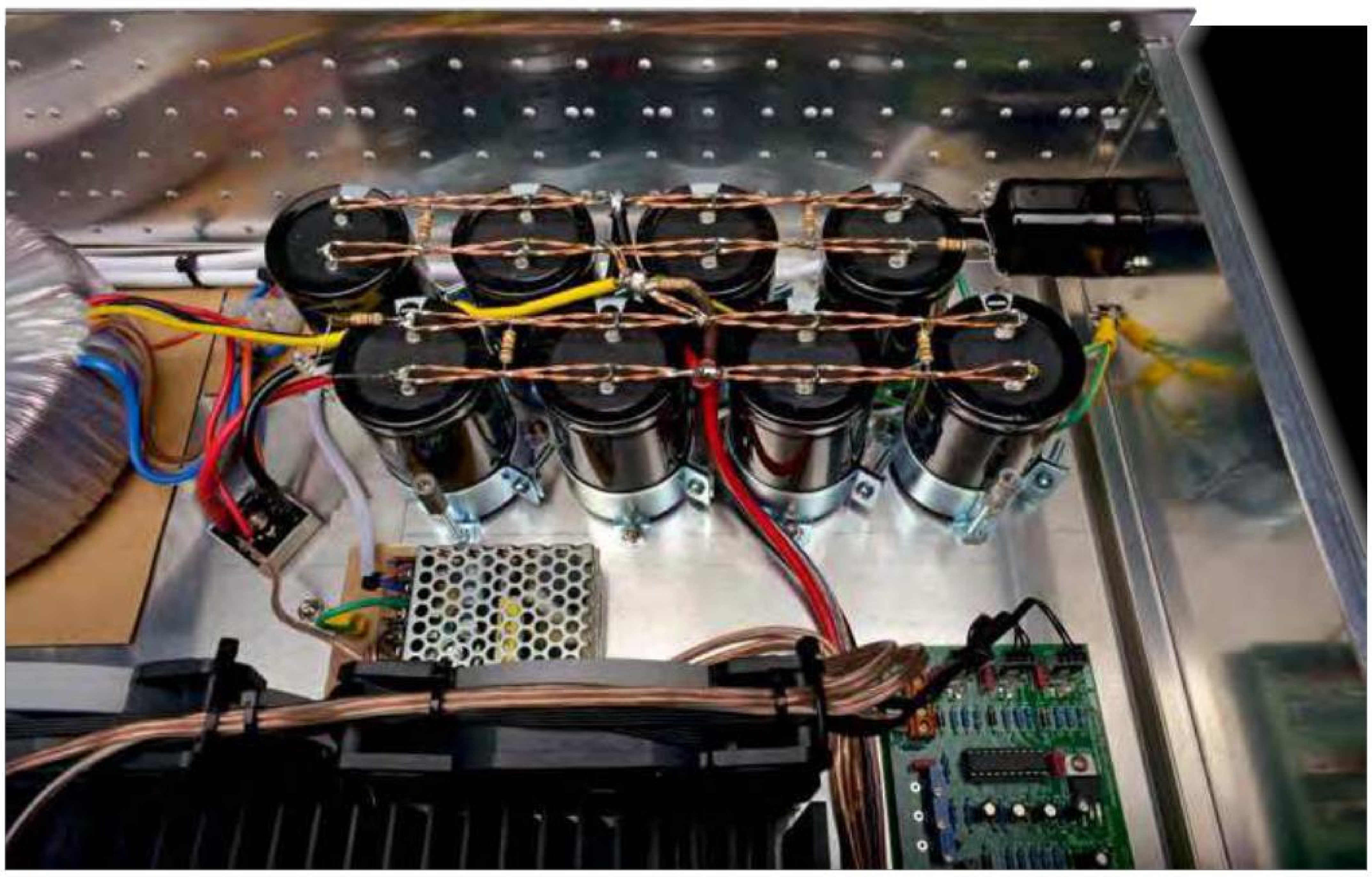

IEC connector with fuse
N
E
A
INSULATION BOOT SHOWN TRANSPARENT
REAR PANEL (inside view)
M4 screw, star washer & nut
Earth
Cable Tie
M4 screw, star washer & nut
Earth
* M4 x 50mm screws, nuts and M4 tapped joiner to support capacitor top covering
Capacitor top covering is shown transparent
LED5
A
Negative polarity marking
Cable Tie
+80V
Star earth point
–80V
4 strands each of 0.5mm diam. copper wire
12V SUPPLY
A
N
E
0V
12V
15kΩ 1W
10,000µF Capacitor
LED4
A
Panel Mount cable tie
Insulation Board

Fig.13: a close-up of the chassis' left rear corner showing the wiring of the capacitor bank, 12V switch-mode supply, mains IEC input socket and the earthing.

Now you can complete the remaining wiring. Run the wiring from the filter capacitors to the *Amplifier* using the 2.9mm^2 wire, with red for positive, black for negative and one of the 2.93mm^2 figure-8 wires for the 0V connection.

Similarly, use 2.9mm^2 or 2.5mm^2 wire for the loudspeaker output wiring to the speaker terminals via the relay.



For safety, the capacitor bank needs a sheet of perspex mounted on top of it to prevent accidental contact. This photo shows the capacitors without the cover, to clearly present how they are arranged.

The rest of the wiring can use lighter-duty wire. Follow the wiring diagram carefully to complete it. Use cable ties and chassis mount ties to bundle wires together where needed. We don't show all the cable ties on the diagram; be generous and use them wherever required.

Connect the XLR input socket to the amplifier module via dual-core microphone shielded cable, as per Fig.15. If using an RCA input socket instead, use single-core shielded cable.

Now attach the side, rear and front panels to the baseplate.

Final checks and adjustments

You are now ready to power up the *Amplifier Module* and make voltage checks. First, double-check all your wiring against the circuits and diagrams in this series of articles. Then reattach the capacitor safety shield.

Remove fuses F1 and F2 on the *Amplifier Module* and replace these with blown fuses with 390Ω 5W resistors soldered across the fuse ends. Ensure that trimpot VR2 is rotated fully anti-clockwise.

Apply power and measure the voltage on the *Amplifier* speaker output, at one of the 56Ω 1W resistor ends closest to the edge of the *Amplifier* PCB. There should be less than ±20mV DC at the output. You can adjust this using VR1, to get a reading close to 0V.

Now connect your multimeter across the 390Ω 5W resistor across fuse F1, and adjust trimpot VR2 clockwise to obtain 30V. This provides a total quiescent current of 77mA or about 13mA per output transistor.

Now measure the voltage across the other 390Ω 5W resistor in place of fuse F2. It should be within 10% of the reading across F1.

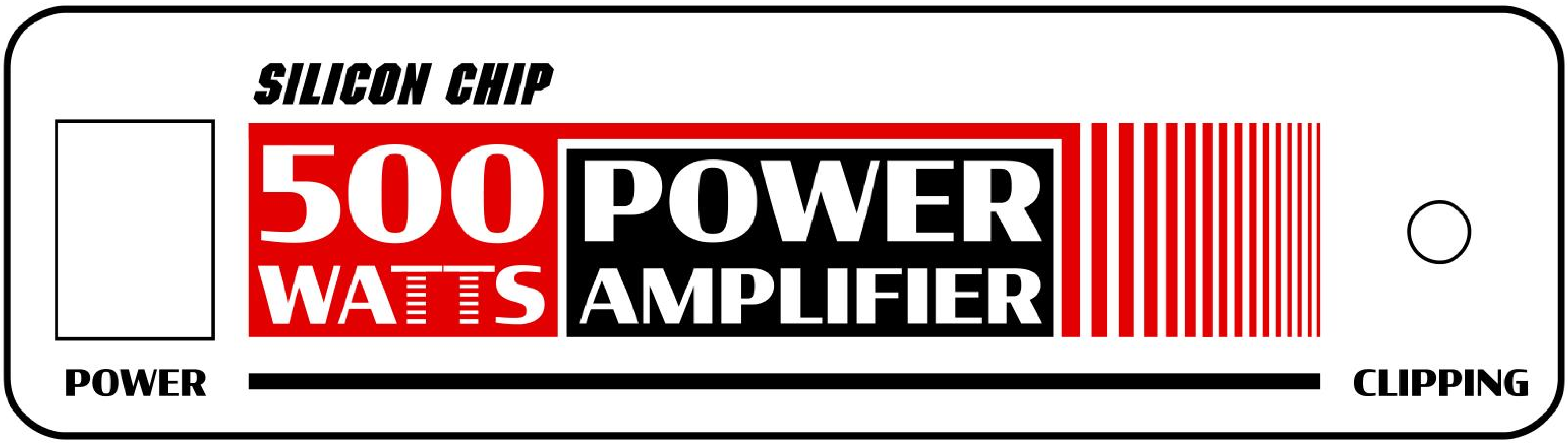
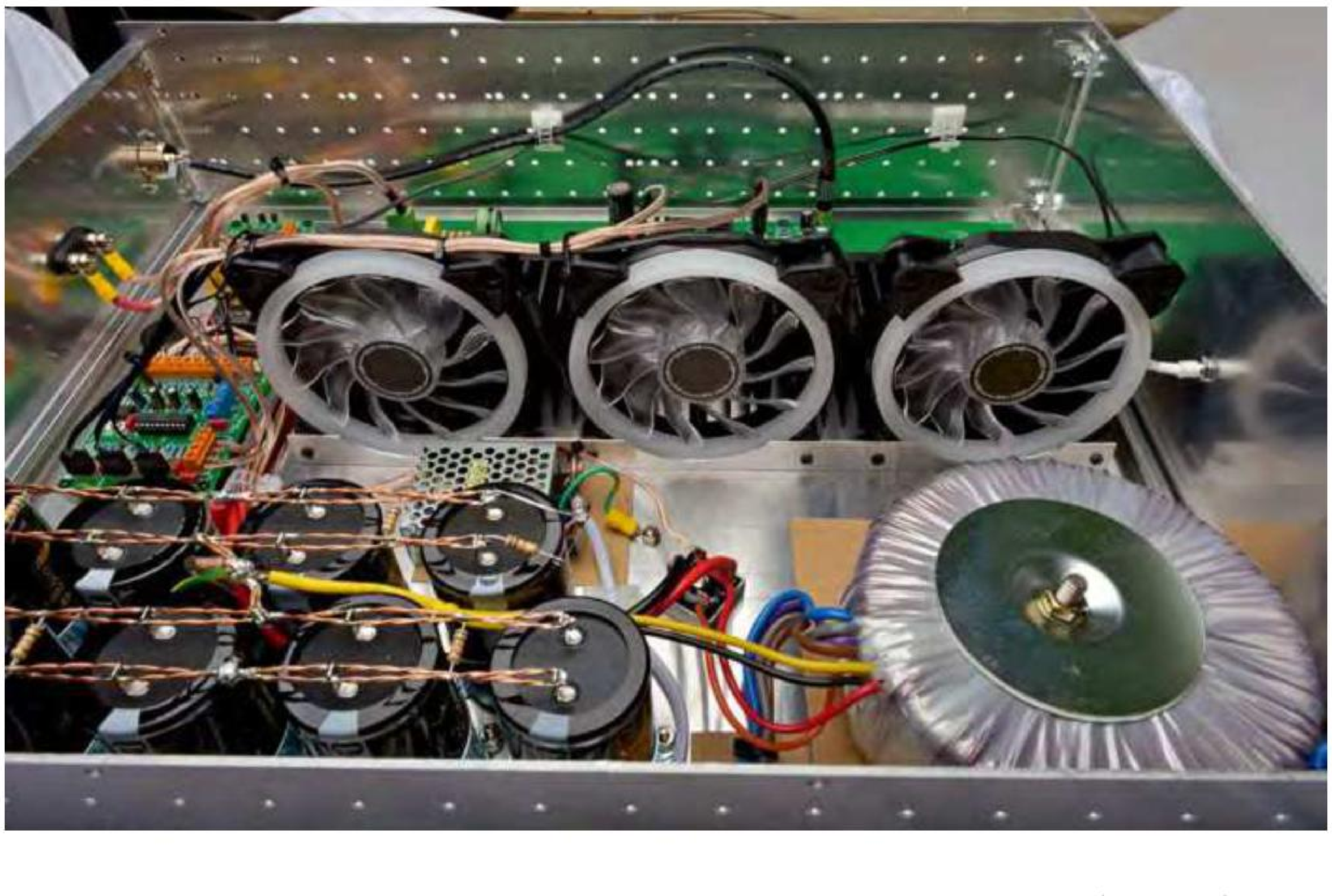
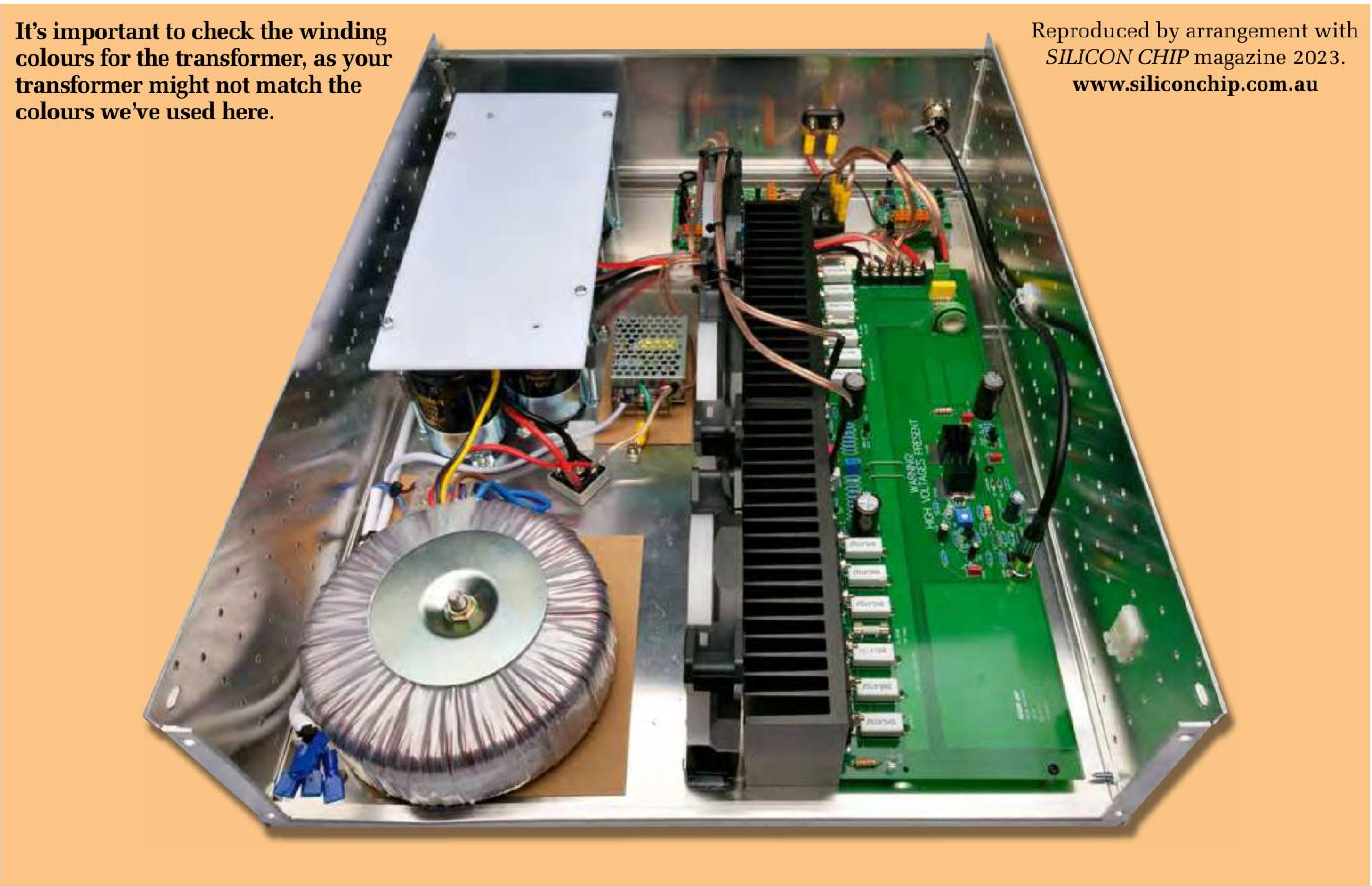


Fig.14: the front panel label (shown at 85% actual size) can be used as a template to drill the holes for the power switch and the clipping indicator LED. Or, download a copy from the June 2023 page of the *PE* website at: https://bit.ly/pe-downloads and print it on overhead transparency film or photo paper (laminated after printing) and affix it to the front of the *Amplifier*. This label only covers the left-hand half of the panel, as it would be too wide to easily print otherwise.

The 120mm PWM fans for the 500W *Amplifier* are attached via a metal bracket on the base of the case. These types of fans are quite common in computers, and be purchased at low cost. Smaller fans (eg, 80mm) could be used, but they will probably be louder and, due to how common 120mm fans are, likely more expensive too.





It's important to check the winding colours for the transformer, as your transformer might not match the colours we've used here.

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You now need to leave the *Amplifier* running for at least an hour. This will allow it to warm up gradually. Measure the voltage across the 390Ω resistors again and readjust VR2 to give 30V.

Troubleshooting

If these voltages cannot be realised, switch off the power and recheck your construction and wiring. You will need to measure voltages around the *Amplifier Module* to see where there could be a problem. To do this, first reduce the quiescent current by turning VR2 anti-clockwise so that there is minimal voltage across the 390Ω resistors that are across each fuse holder.

First, check for +80V, 0V and −80V at the *Amplifier Module* supply terminals. Check the voltages across the 470Ω resistor at Q5's emitter and the 39Ω resistor at Q7's emitter. If these aren't between 0.6 and 0.8V, check transistors Q5 and Q6 for about 0.6-0.7V between the base and emitter of each. If not correct, verify that they are the right transistor types.

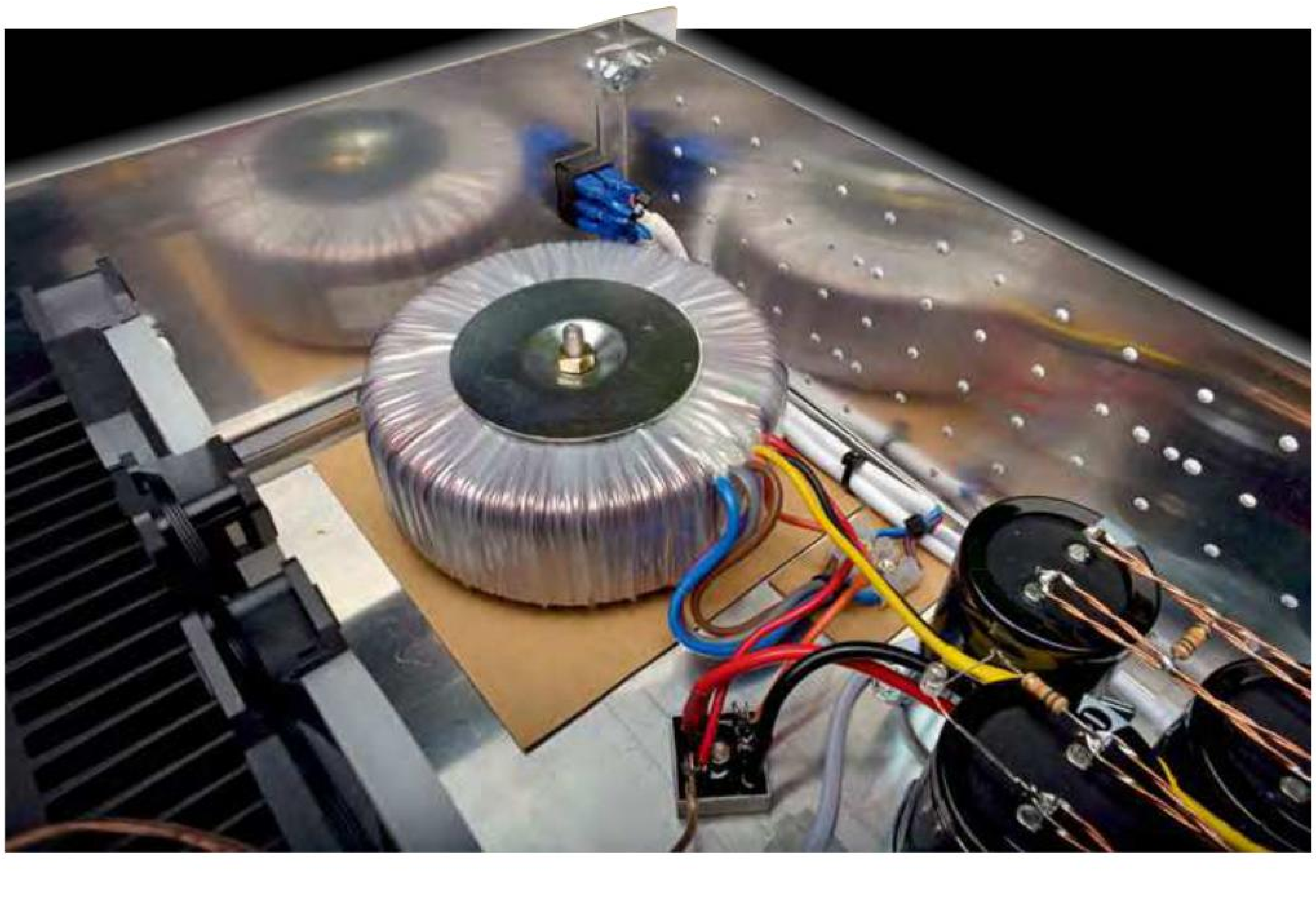
Additionally, the voltages across the 68Ω emitter resistors for Q3 and Q4 should be about 50-60mV each, and both voltages should be the same provided VR1 is adjusted for minimum output offset. If these are not correct, check the transistors for the correct type.

If the correct transistors are in place, but the voltages are incorrect, consider replacing these transistors with reputable brand-name devices.

Once the problems are found/fixed, you can adjust the quiescent current again for 30V across the 390Ω resistors.

When it all checks out, power it down, wait for the capacitor banks to fully discharge, then remove the fuses with the 390Ω resistors attached and install the correct ceramic fuses; 5A for use with 8Ω speakers or 10A for 6Ω or 4Ω speakers.

Finally, follow the instructions for setting up the *Fan Controller & Loudspeaker Protector* in the February 2022 issue.



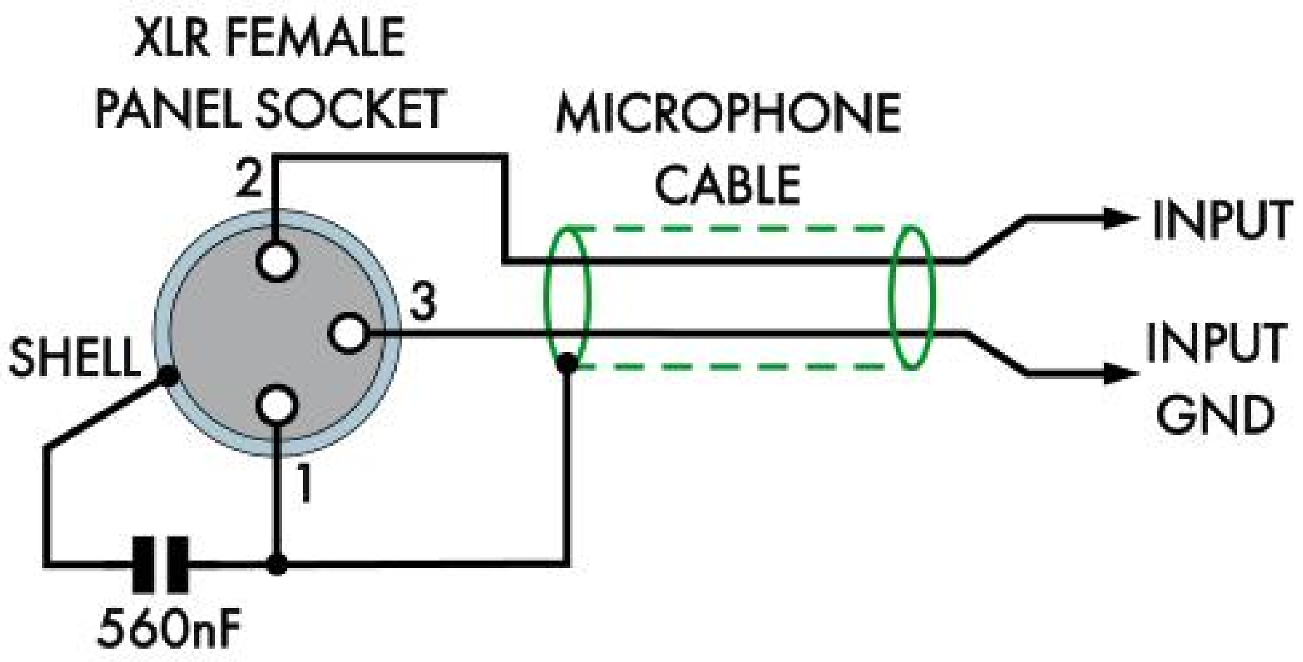
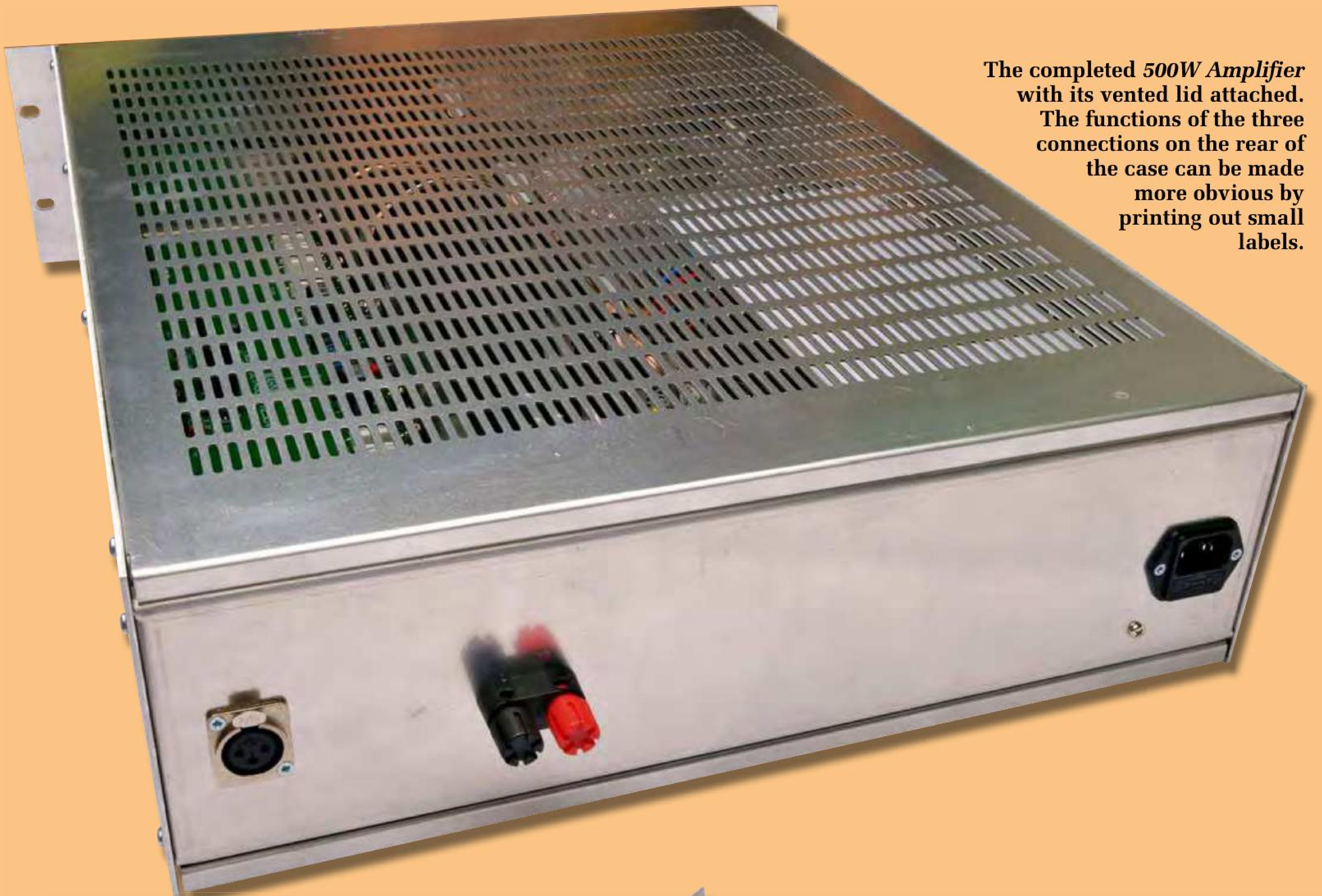
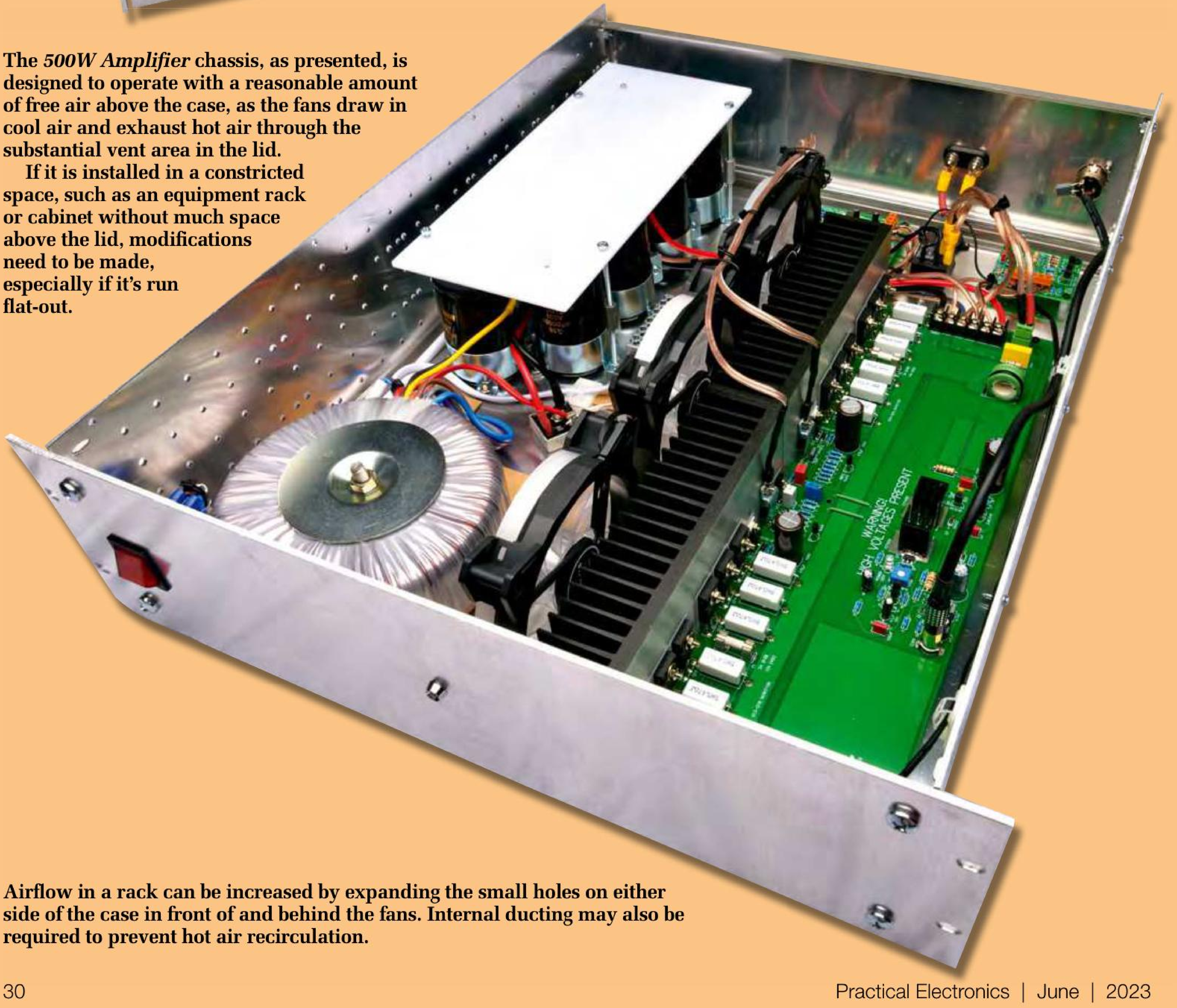


Fig.15: the wiring details for the XLR socket. For home use, an RCA socket could be fitted instead, in which case you could even use a panel-mount female-female RCA socket. A standard RCA cable can then connect from the inside of this socket to the *Amplifier Module* input, thereby avoiding soldering.



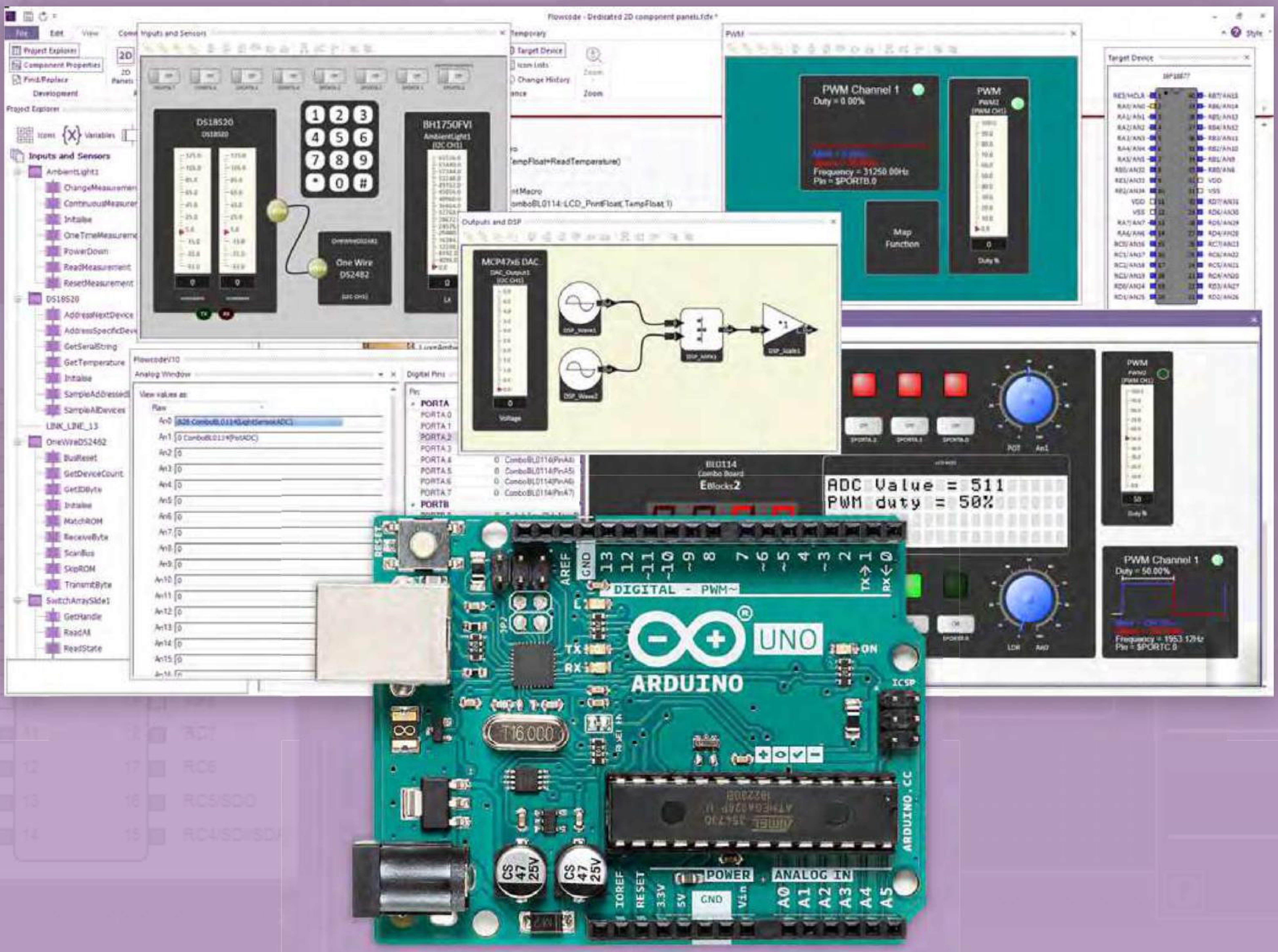
The completed *500W Amplifier* with its vented lid attached. The functions of the three connections on the rear of the case can be made more obvious by printing out small labels.



The *500W Amplifier* chassis, as presented, is designed to operate with a reasonable amount of free air above the case, as the fans draw in cool air and exhaust hot air through the substantial vent area in the lid.

If it is installed in a constricted space, such as an equipment rack or cabinet without much space above the lid, modifications need to be made, especially if it's run flat-out.

Airflow in a rack can be increased by expanding the small holes on either side of the case in front of and behind the fans. Internal ducting may also be required to prevent hot air recirculation.



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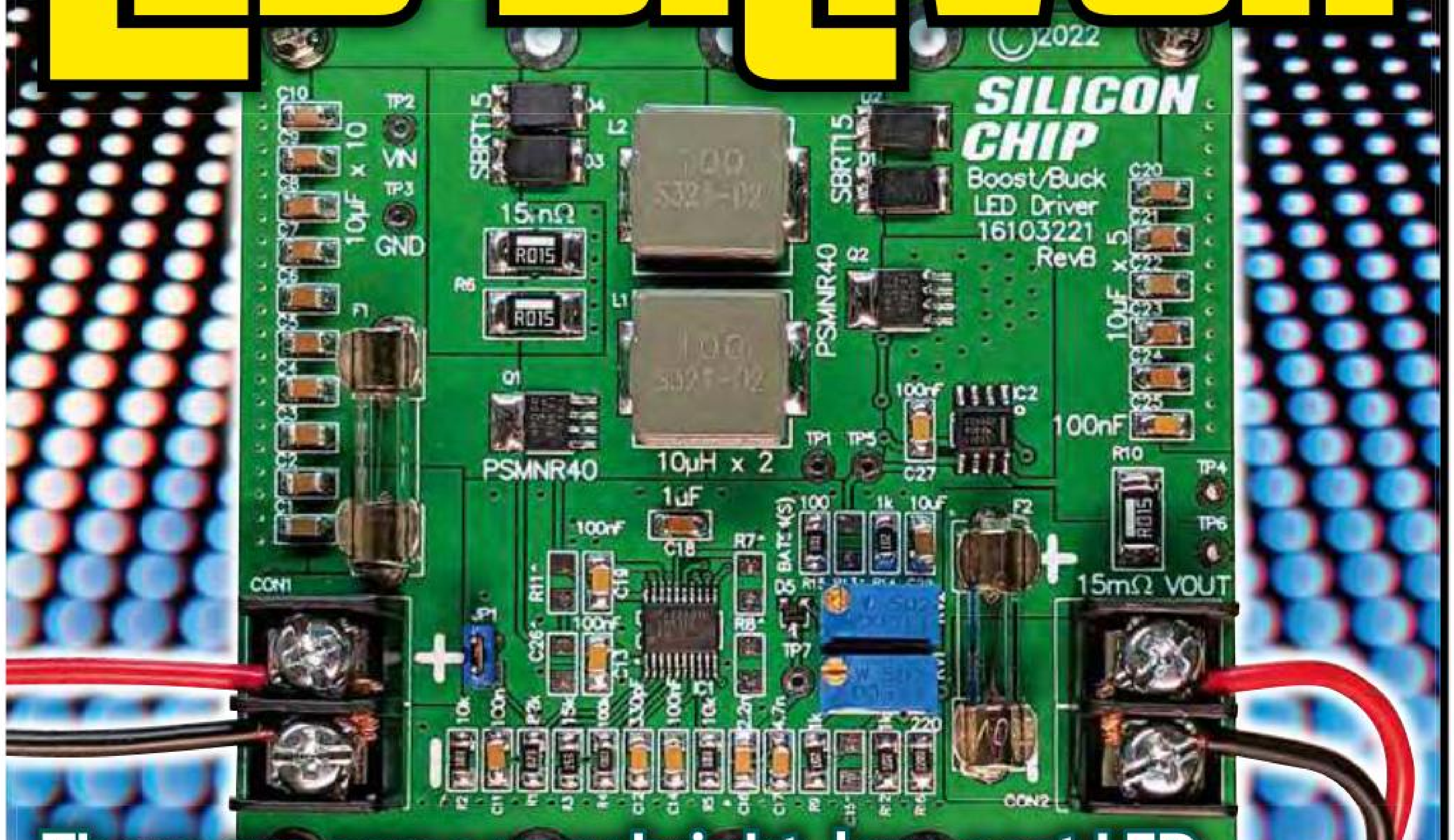
High-Power Buck-Boost LED Driver



There are some very bright, low-cost LED panels for sale, and we've been figuring out the best way to drive them. This Driver is the result; it is flexible and useful for many other purposes, such as charging batteries from a DC source or converting between 12V DC and 24V DC.

By Tim Blythman

Background Source: https://unsplash.com/photos/k4KZVfAXvSg

For around a fiver, you can buy impressive LED panels from AliExpress (eg, **www.aliexpress.com/item/4001275542304.html**). They measure about 22cm by 11cm with an active area of 20cm by 10cm. They're also available from other online sellers such as eBay or Banggood.

The panels are based on an aluminium PCB and have a silicone gel coating over the LED array. They are specified as drawing 70W at 12V DC, and they simply expose two solder pads for the power source.

Features and Specifications

- Switch-mode buck-boost current/voltage driver module
- Suitable for driving a variety of 12V LED panels
- Adjustable current and voltage settings using trimpots
- Alternative fixed voltage/current settings with fixed resistors
- Lower-cost 5A option by omitting some parts
- Input voltage range: 11.3V-35V
- Output voltage range: 7-34V
- Maximum output current: 8A
- Maximum input current: 10A
- Other uses include charging a 12V battery from another 12V battery or other DC source
- Can also be used as a 12 ➔ 24V DC or 24 ➔ 12V DC converter

There are several other modules with different sizes and power ratings, although we haven't tested any of those alternatives.

Having received some samples of these LED panels, we ran some tests using our *45V Linear Bench Supply* (October-December 2020) and produced the current/voltage curve seen in Fig.1. This is consistent with four groups of LEDs arranged in series, each with a voltage drop of around 3V, giving a forward voltage of about 12V.

Running the panel at 50W (close to 4A) for a while, it got pretty hot and was way too bright to look at directly. So we expect that these panels can be run at lower power levels than that and still be very useful. Running them cooler should also extend their working life.

When supplied with a small amount of current, the individual LEDs can be seen, and there are 336 of them, arranged in 28 rows of 12. Each group of LEDs connected in parallel corresponds to seven rows.

YouTuber Big Clive ran some tests on similar modules, and even tore back the gel coating to see what lies beneath. You can watch his video at: **https://youtu.be/uIspnsBp3o4**

He found that each group of LEDs is simply wired in parallel, meaning that the panel is mostly unaffected if one LED fails open-circuit. A short-circuit failure would tend to shunt the entire panel current through a single LED, quickly turning it into an open circuit!

It also appears that the LEDs are actually blue, and the gel is a phosphor coating. It's an interesting construction that is quite robust, but simple and clearly cheap to manufacture.

As LEDs are often touted as being around eight times more efficient (in terms of lumens per watt) than incandescent globes, 70W of LED light is equivalent to several hundred watts of incandescent light; easily enough to illuminate a large room very brightly.

Limitations

It's evident from the current/voltage curve that applying much more than 13V will put the panel over its nominal 70W limit. So directly connecting a 12V battery, which could supply as much as 14V or higher, is not a feasible way to drive these panels.

A 12V battery that's nearly flat might only produce around 11.5V, so a resistive voltage dropper is not suitable for powering these panels over a battery's useful charge range.

We also expect the current/voltage curve to change depending on the panel temperature. That will change during operation as the panel self-heats due to its own dissipation.

Like most LEDs or LED arrays, a current-controlled or current-limited supply is the best choice for driving this one. While the voltage may drift slightly under constant current conditions, it's a much more stable arrangement. Thus our *Driver* incorporates current-control circuitry.

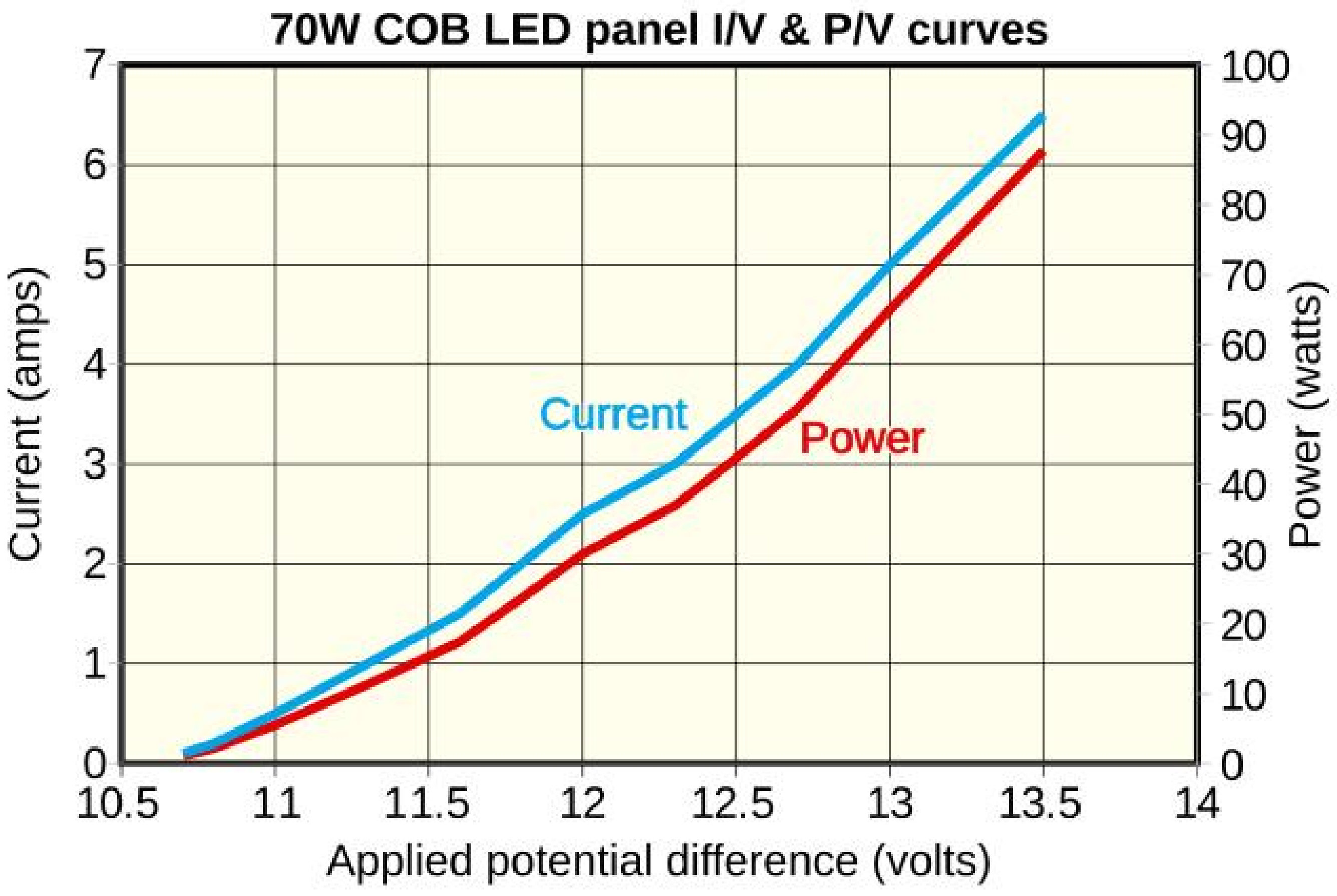


Fig.1: like any semiconductor diode, the current through these LED panels changes sharply with changes in voltage. As such, it's not practical to regulate the panel brightness by controlling the voltage. We must instead control the current, one of the features of the LED Driver PCB.

The LED Driver

Given that a common use case would be running these LED panels from a 12V battery or DC supply, we need a few specific features. The LED panel operating point might be above or below the battery voltage, so we need to be able to increase or decrease the incoming supply. And to provide a consistent level of lighting, we also need to regulate the output current.

For efficiency, we need to use a switch-mode circuit. For this to both increase and decrease the voltage, it needs to be able to either buck (reduce) or boost (increase) the incoming voltage.

Some circuits do this by having two separate stages; for example, first by decreasing the input voltage as needed and then using a second stage to boost the output from the first stage. The design of such circuits can be complex; more so when current limiting or regulation is needed. However, chips exist that can work in boost or buck mode as needed; for example, the LM5118.

The LM5118 handles the transition from boost to buck mode by using a hybrid mode that is somewhere in between at intermediate voltages, ensuring that the output remains stable at all times.

It does provide current limiting, but only to protect the inductor that is used to store energy during the boost and buck phases. So we needed to add some parts to the design to provide independent, adjustable output current limiting.

Circuit details

Fig.2 shows the circuit that we have designed incorporating all these features. Parts of it look similar to the *Hybrid Bench Supply* because of the common external parts needed for the LM5118 to operate.

Power comes in through a two-way barrier terminal, CON1, with the positive supply passing through 10A fuse F1. The 10A limit was chosen as a convenient level above the 7A limit of the LED panel.

A bank of paralleled ceramic 10µF capacitors provides bulk supply bypassing to the power section of the circuit, while a 100nF capacitor is placed close to IC1, the LM5118, to stabilise its supply.

The VIN supply feeds into pin 1 of IC1 with grounds at pins 6 and 14. An 82kΩ/10kΩ divider across this supply to IC1's pin 2 UVLO (under-voltage lock-out) exceeds its threshold of 1.23V when VIN is around 11.3V. This way, if a battery is used to feed the circuit, it will be prevented from discharging below 11.3V, a fairly conservative level for most lead-acid batteries.

The 15kΩ resistor between pin 3 of IC1 and ground sets the boost/buck oscillator frequency to around 400kHz, which gives decent efficiency and low voltage ripple at the output.

IC1's pin 4 (EN) is pulled to ground by a 100kΩ resistor, but can be pulled up to VIN by shorting the pins of JP1. Thus, JP1 can be closed with a jumper to provide 'always on' operation, or connected to an external low-current switch to give a simple on/off control.

The capacitors on pins 5 and 7 (RAMP and SS) set the ramp and soft-start characteristics of IC1 to be suitable for our application.

IC1's pin 8 FB (feedback) input is used to set the output voltage. The divider formed by potentiometer VR1 and its two series 'padder' resistors feeds that pin with a fraction of the output voltage that is compared with a 1.23V reference within IC1.

This adjustment gives a nominal output range between 6.8V and 34.7V. The 34.7V upper limit is chosen to stay well clear of the 60V MOSFET V_{DS} limit for Q2 while maintaining a useful range for 24V systems. The 1kΩ resistor between the divider and the FB pin reduces the interaction between the voltage control and current limiting, which we will explain shortly.

The 2.2nF capacitor, 4.7nF capacitor and 10kΩ resistor between pins 8 and 9 are a compensation network that forms part of the feedback loop that controls IC1's duty cycle.

IC1's pins 12 and 13 connect across a pair of current-measuring shunts to monitor the current through D3 and D4, thus limiting the current through L1 and L2. This works whether the circuit is operating in boost or buck mode.

Pins 19 (HO) and 15 (LO) drive the external high-side (Q1) and low-side (Q2) MOSFETs, respectively. Pin 16 is connected to an internal regulator that provides around 7V with an external 1µF capacitor to stabilise this.

The 7V supply is used to drive the MOSFET gates and is a good compromise between turning them on fully while maintaining fast switching. It also powers shunt monitor IC2, which we'll get to shortly.

Pins 18 (HB) and 20 (HS) are connected to either end of a 100nF capacitor, which is charged and then used

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These panels are incredibly bright, too bright to look at directly when set to anything but the lowest setting. When the panel is off, you can just make out the numerous small LED chips that provide the light output under the phosphor gel coating.

to drive the HO pin above the supply voltage. This 'floating' gate supply is needed to switch on the high-side N-channel MOSFET as its source terminal can be at or near the supply voltage when it is switched on.

MOSFETs Q1 and Q2, inductors L1 and L2 and diodes D1-D4 are arranged in a bridge-like configuration that can be driven in either boost or buck switching modes. Fig.3 shows how such a bridge can work in both modes.

The circuit works as a buck switcher for low output voltages (compared to the input voltage). When Q1 is on, current flows through L1 and L2 and then D1 and D2 towards the load. When Q1 switches off, the current continues to circulate via D3 and D4.

Above 75% duty cycle on Q1, IC1 operates in the hybrid boost-buck mode. Q2 starts to switch on with a duty cycle that overlaps with Q1's on-time. This increases the current through the inductors during the on-time, and this extra energy gets fed to the output during the MOSFET off-time, increasing the output voltage.

A simple implementation of the boost mode would have Q1 on all the time boost mode is active, but this is not possible with the LM5118, so it is switched on and off in synchrony with Q2.

This is necessary because the bootstrap capacitor needs to be periodically refreshed to maintain the gate voltage, which can only happen while Q1 is off.

All this is done transparently by the controller inside the LM5118.

Current limiting

The voltage at the cathodes of D1 and D2 is smoothed by a bank of five 10µF capacitors accompanied by a 100nF capacitor. From there, it passes through another 15mΩ current-sensing shunt, then through fuse F2 to output connector CON2.

We can keep the grounds common between the input and output by placing the current shunt in series with the positive output. This has several advantages, one of which is that you don't need to have the ground current pass through this module; it can go straight from the load to the power source, possibly simplifying the wiring and reducing wire-related power loss.

The voltage across the shunt is measured by IC2's pins 1 and 8 and amplified with a gain of 50. IC2 is an INA282 current shunt monitor, and it takes its supply on pin 6 from IC1's internal 7V regulator. It also has its own 100nF supply bypass capacitor.

IC2's pins 3 and 7 are both connected to ground, so the output voltage from pin 5 is relative to ground. The voltage at pin 5 is divided and smoothed by the network consisting of the 100Ω resistor, 5kΩ trimpot VR2, 1kΩ resistor and 10µF capacitor.

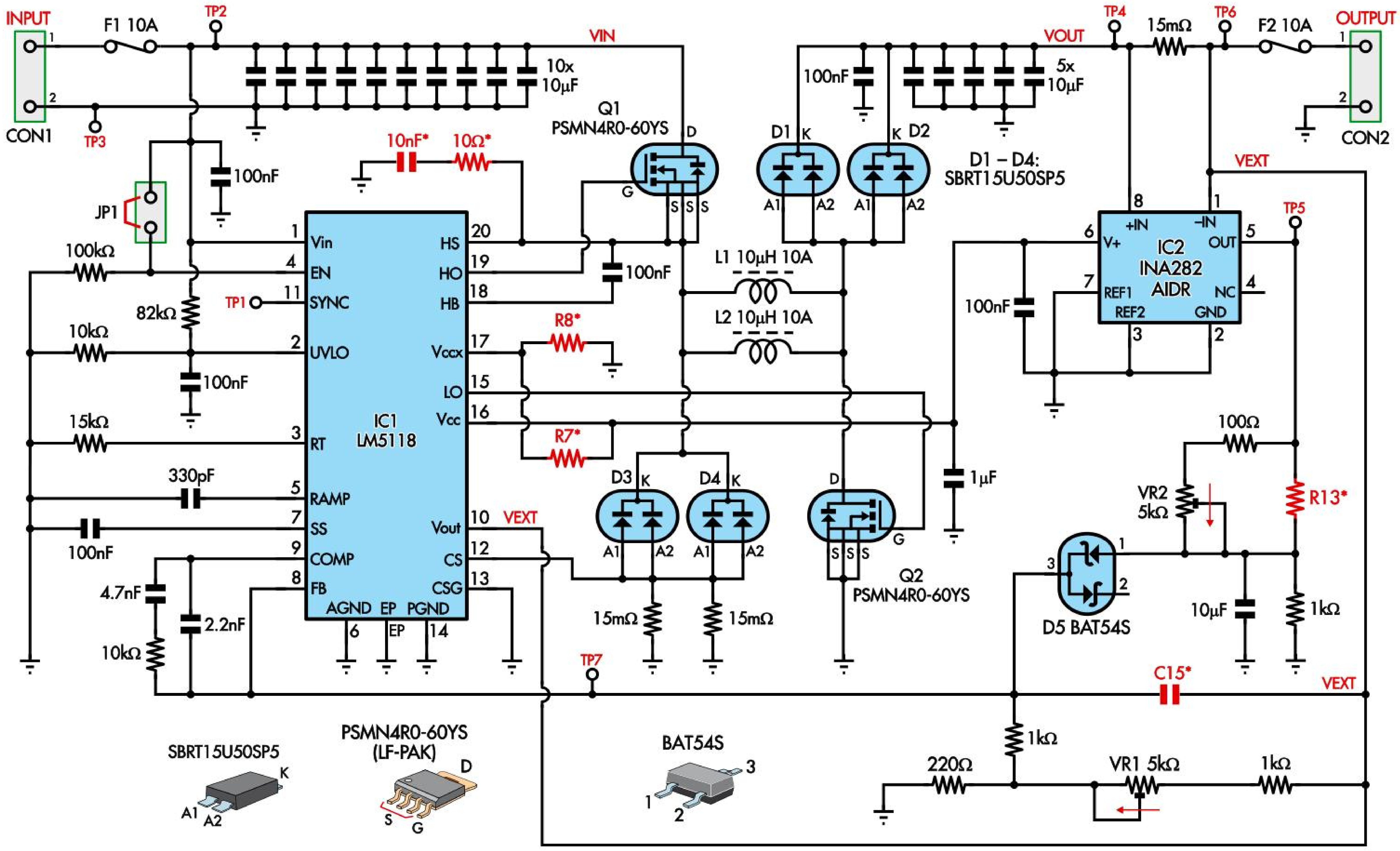
The smoothing is necessary to eliminate instability which would cause LED flickering due to oscillations in the output voltage.

The resulting voltage is fed into IC1's FB pin via schottky diode D5. Thus, as the output current increases beyond a certain threshold, the voltage at the FB pin increases similarly to the situation where the output voltage is too high. IC1 attempts to control this by reducing its output voltage, thus reducing the current.

The diode ensures that an output current below the limit does not drag down the reference. If the target current is not met, the control loop is based only on the output voltage.

The result is not a 'brick wall' current limit; it allows higher currents at lower output voltages. This is because a higher voltage is needed at D5 to maintain balance at the FB pin as the output voltage drops further below its setpoint.

The 1kΩ resistor between VR1 and the FB pin helps maintain this balance and limit the extent to which the two parts of the circuit interact.


INPUT
F1 10A
TP2
VIN
10x 10µF
VOUT
TP4
15mΩ
TP6
F2 10A
OUTPUT
CON1
TP3
CON2
5x 10µF
100nF
Q1 PSMN4R0-60YS
D1
D2
D1 – D4: SBRT15U50SP5
VEXT
10nF*
10Ω*
JP1
100kΩ
82kΩ
TP1
10kΩ
15kΩ
330pF
100nF
4.7nF
2.2nF
10kΩ
IC1 LM5118
Vin
EN
SYNC
UVLO
RT
RAMP
SS
COMP
FB
AGND
EP
PGND
HS
HO
HB
Vccx
LO
Vcc
Vout
CS
CSG
R8*
R7*
L1 10µH 10A
L2 10µH 10A
IC2 INA282 AIDR
+IN
–IN
V+
OUT
REF1
REF2
NC
GND
TP5
100Ω
VR2 5kΩ
R13*
1µF
D3
D4
Q2 PSMN4R0-60YS
15mΩ
15mΩ
D5 BAT54S
10µF
1kΩ
TP7
C15*
1kΩ
220Ω
VR1 5kΩ
1kΩ
SBRT15U50SP5
PSMN4R0-60YS (LF-PAK)
BAT54S
A1
A2
K
S
G
D

*NOTE: COMPONENTS SHOWN IN RED ARE OPTIONAL – SEE TEXT

Buck-boost LED Supply

Fig.2: the circuit is based around IC1, an LM5118 buck-boost controller. It drives the H-bridge made from MOSFETs Q1 and Q2, diodes D1-D4 and inductors L1 and L2. These allow it to step down the incoming voltage (by pulsing Q1 on) or step it up (by pulsing Q1 and Q2 on simultaneously). Varying the duty cycle/on-time allows it to change the output-to-input voltage ratio. We've added IC2 and some other components to provide an adjustable current limit.

With VR2 at its minimum setting, an output current of 1.8A will induce 27mV across the shunt or 1.35V at pin 5, which corresponds to 1.23V at the divider output, meaning that this is the point that current limiting begins. With VR2 set higher, a smaller fraction of the pin 5 voltage is sampled, and thus a higher output current is allowed.

In practice, since IC2's supply is around 7V, the maximum current setting is around 8A. So setting VR2 above around ¾ of its travel will effectively disable the current limiting.

Lower output current settings can be achieved by increasing the shunt resistance, although that would arguably be a poor use of a circuit capable of 8A.

That the current limit tapers off is actually an advantage as it tends to put the system closer to constant-power operation. For the LED panels, the operating voltage range will be quite narrow in any case.

Pairs of parts

You might notice from the schematic that a few parts are duplicated and paralleled. These include L1 and L2, D1-D4 and the 15mΩ current shunts connected to D3 and D4. The circuit has been designed with these extra parts to handle up to 8A, by splitting the current between the pairs of components and thus moderating the heating of any single part.

For operation up to 5A, L2, D2, D4 and one of the shunts can be omitted. The input and output fuses should also be changed to suit 5A operation. All other components can work happily up to the 8A limit.

While the shunt resistors do not dissipate any significant amount of power, they are used by IC1 to monitor the current through the inductors. Whether one inductor and one shunt or two inductors and two shunts are present, the current limit through each inductor is the same.

Extra parts

There are a few component locations that are usually left empty. These are shown in red on the circuit and PCB overlay diagram. We've incorporated these in the design as they are shown in the application notes for the LM5118, and are useful in certain situations.

We were initially unsure whether these parts were needed for stable operation, but it turned out they were not. Some enthusiastic readers might be tempted to experiment with the design and use these component locations, as shown in the LM5118 data sheet.

The optional parts include an RC snubber for the switching node and components to disable IC1's internal regulator if the input supply voltage will always be within a suitable range (about 5-15V).

Since the LM5118 can operate up to 76V (with some parts changes needed in our design to achieve that), this board would have many potential applications. Some configurations may not be as stable as the one presented here, so figuring out what components are needed in different use cases is left as an exercise for the reader.

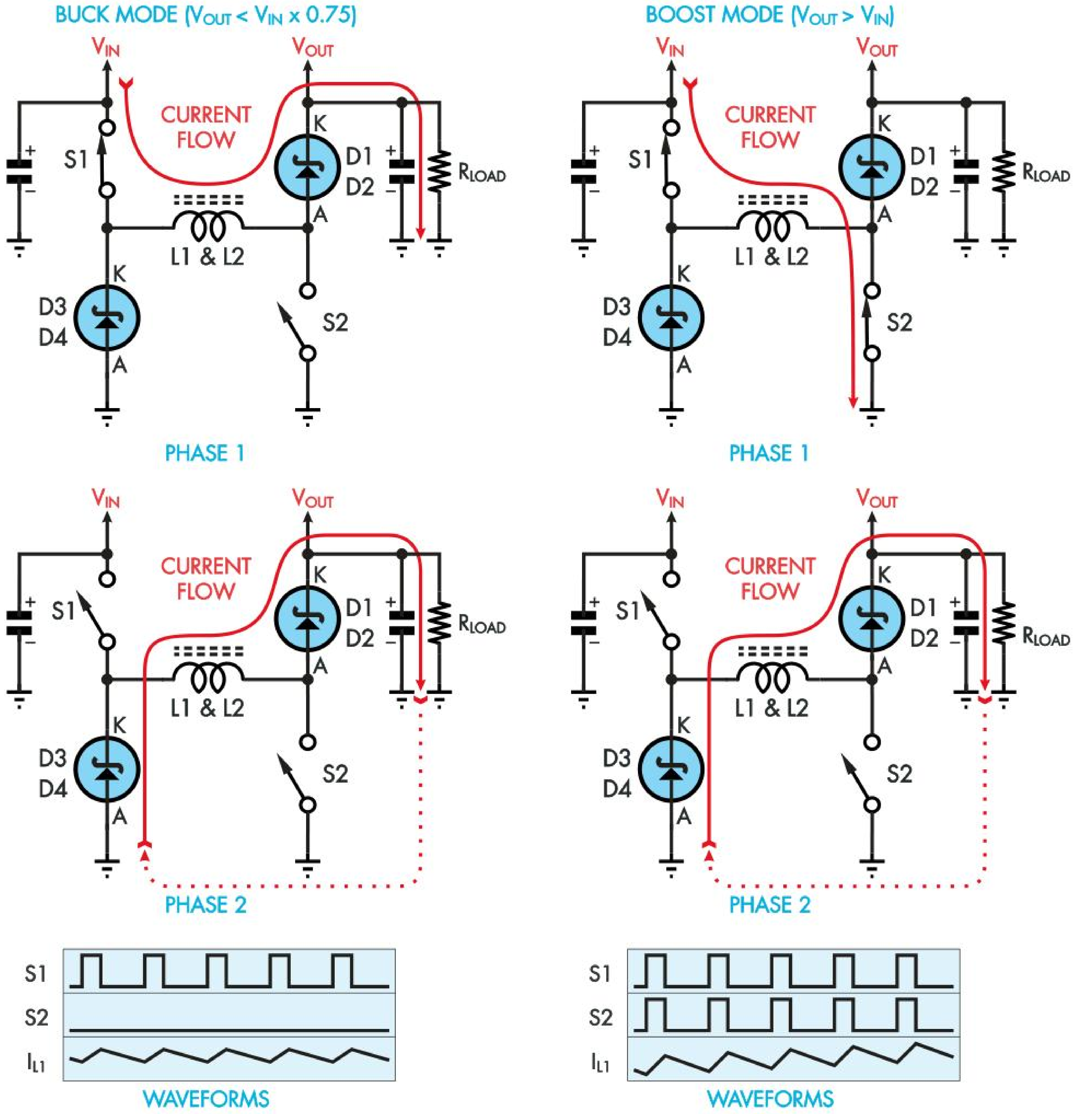
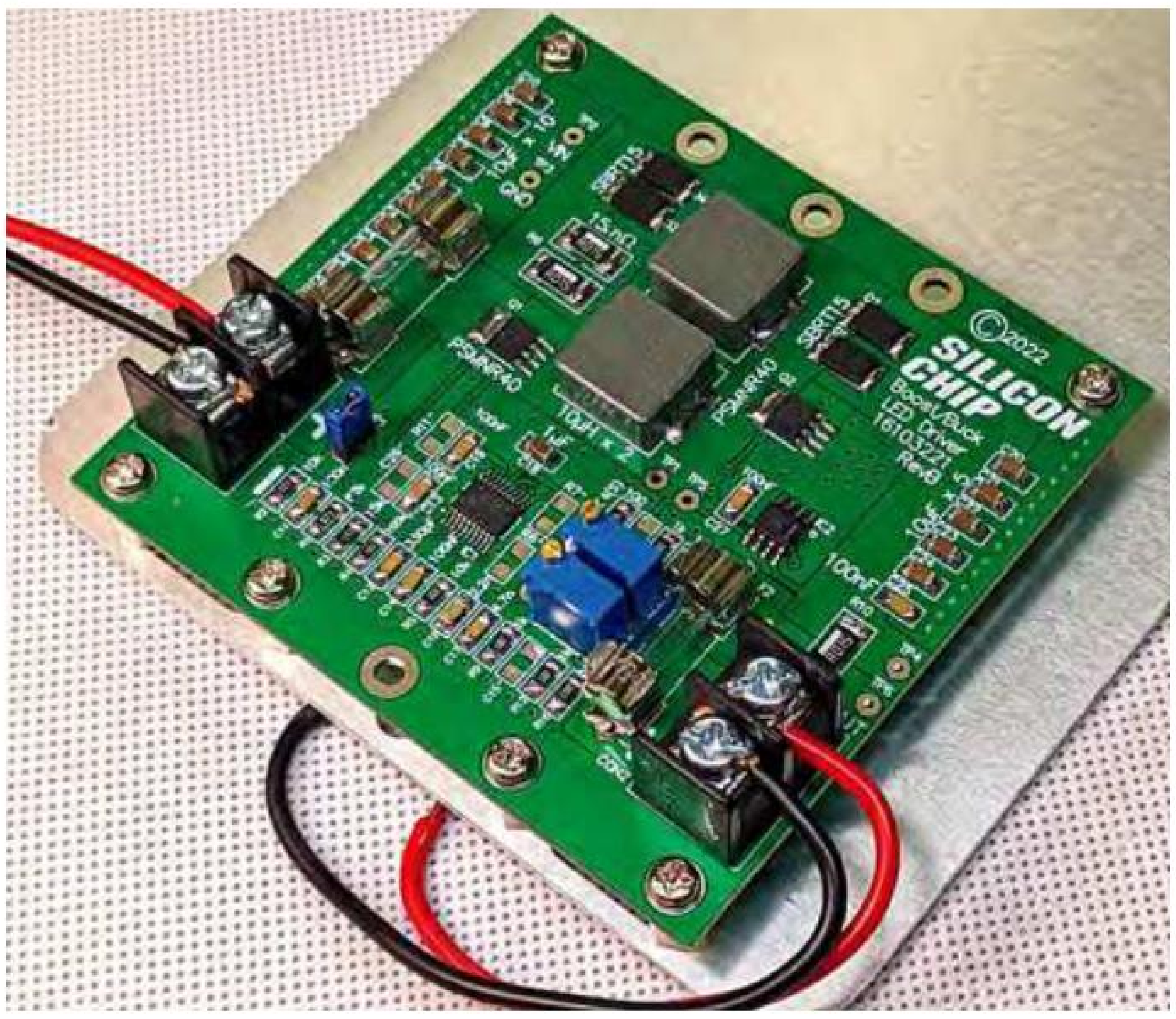


Fig.3: an illustration of how the LM5118 works: in buck mode (diagrams at left) and boost mode (at right). The mode of operation is determined by whether S2 (actually a MOSFET) is switched with S1 or just left open (ie, off). In buck mode, as the duty cycle approaches 100%, the output voltage approaches the input voltage while in buck/boost mode, a 50% duty cycle gives an output voltage equal to the input with higher duty cycles boosting the output voltage above the input, approximately doubling it at 75% duty, quadrupling it at 87.5% and so on.



The LED Driver is designed to mount directly to the 70W LED panels, with just two flying leads between the two. As it has many other potential uses, you can mount it in just about any kind of box using tapped spacers.

Options

R13, adjacent to VR2, is a different case. This fixed resistor is intended to replace VR2 for a fixed setpoint. Alternatively, you can replace either VR1 or VR2 with a fixed resistor between their two leftmost terminals, as they are simply wired as variable resistors (rheostats).

Table 1 shows typical resistor values for fixed output voltages, including the exact and nearest E24 series values. The values are linear across the range, so you can interpolate them to find intermediate values if necessary.

Table 2 does the same for current, with the listed values being at the point that current limiting first kicks in. Similarly, exact and nearby E24 series values are given, and the correlation is relatively linear.

Battery charging

Although we have not done thorough testing with this configuration, the *Driver* is well-suited for charging a 12V battery from another 12V battery. This might seem like an unusual requirement, but it often crops up in situations involving a caravan or similar that has a 'house' battery, usually a deep-cycle type.

Such a battery is typically charged from the 12V system of a towing vehicle while the vehicle is charging its starter battery. Due to voltage drops over long cables and the tendency of modern vehicles not to fully charge their starter battery, there may not be enough volts available to fully charge such a house battery via a direct connection.

The *Driver* can overcome this and comfortably deal with batteries in all charge states due to the current limiting feature. The *Driver* is set to provide a voltage that suits the desired house battery's fully charged level, with the current limit set to a safe level for the batteries and wiring.

A diode or VSR (voltage-sensitive relay) on the *Driver's* output may be necessary to prevent the house battery from draining through the *Driver's* voltage sense divider. Note that the *Driver* should be located close to the house battery so that cable resistance does not affect sensing the house battery voltage.

Construction

The *LED Driver* is built on a double-sided PCB coded 16103221 available from the *PE PCB Service*. It measures 85mm x 80mm. Fig.4 shows where all the parts go on the board.

This design uses almost exclusively surface-mounted parts of varying sizes, so you will need the usual set of surface mount gear.

A temperature-adjustable iron will help greatly in dealing with the wide range of part sizes that are used. Several of the components connect to solid copper pours (for current and thermal handling) and will likely require the iron to be turned up to a higher temperature to make the joints.

Tweezers, flux, solder wicking braid, magnifying lenses and fume extraction are all important requirements for assembly. Also, since you'll need to keep the iron's tip clean, have a tip cleaner on hand.

Begin construction with the two ICs. IC1 has the finest-pitch leads, so start with it. Apply flux to its pads, then align the part with the pin 1 marker and tack one lead in place.

Use a magnifier to confirm that the part is aligned with the pads and flat against the PCB, then tack the diagonally opposite lead and re-check its position.

Solder the remaining leads one at a time, or by gently dragging the iron tip loaded with solder along the edges of the pins. These techniques depend on loading a small amount of solder onto the iron's tip. Practice is the only way to get this right.

Once finished, carefully inspect the leads for solder bridges. If you see any, add some extra flux paste and then use solder wick to gently remove the excess solder.

Finally, clean away the flux residue with a flux cleaner (or pure alcohol if you don't have one) and a lint-free cloth, then check again with a magnifier to ensure all the pins are correctly soldered, and no bridges are left.

Use a similar technique to fit IC2 to the board. Then mount the smaller passive SMDs (except for the shunt resistors) using a similar approach; their larger pads are a bit more forgiving. Remember that some of these parts are not needed (they're labelled in red in Fig.4).

The main trick here is to avoid touching the iron to one side of the part until you are sure the solder on the other side has solidified, or it might shift out of place.

The SMD capacitors are unmarked, so be careful not to mix them up. It's best to unpack and fit all the capacitors of one value at a time. As some of the capacitors (particularly the 10µF parts) are across ground planes, you might need to turn your iron up to make good joints. Ensure the solder flows both onto the end of the part and onto the PCB pad below.

The solitary SOT-23 part, D5, is a BAT54 schottky diode. With one lead on one side and two on the other, its orientation should be obvious. Just make sure its leads are flat on the board, not sticking up in the air, which would indicate that it's upside-down.

Note that you can substitute a dual BAT54S (series) or BAT54C (common cathode) diode as one of their two internal diodes connects between the same set of pads. The other diode in the package will be unconnected and unused.

The remaining surface-mounting parts are larger, so you might like to increase your iron's temperature before proceeding. Also, they are mostly arranged around the top half of the PCB.

Solder the three larger 15mΩ shunt resistors, then the four power diodes.

Table 1: resistor values for fixed output voltages

Target voltage	Calculated resistance	E24 resistor value	Resulting voltage
8V	210Ω	220Ω	8.05V
10V	568Ω	560Ω	9.95V
12V	926Ω	910Ω	11.91V
14V	1284Ω	1300Ω	14.09V
15V	1462Ω	1500Ω	15.21V
20V	2357Ω	2400Ω	20.24V
24V	3072Ω	3000Ω	23.59V
28V	3788Ω	3900Ω	28.63V
30V	4145Ω	4300Ω	30.86V

Table 2: resistor values for fixed output currents

Target current	Calculated resistance	E24 resistor value	Resulting current
2A	119Ω	120Ω	1.98A
3A	729Ω	680Ω	2.92A
4A	1339Ω	1300Ω	3.93A
5A	1949Ω	2000Ω	5.08A
6A	2558Ω	2700Ω	6.23A
7A	3168Ω	3000Ω	6.72A
8A	3778Ω	3600Ω	7.71A

The diodes have two small leads on one end and a larger one on the other. In each case, the ends with two small leads go towards CON1 while the larger single lead is towards CON2. The pad arrangement on the PCB should make this clear.

Solder these like the passives, but take extra care that the part is aligned correctly so that the large tab that runs under the part does not short onto the smaller pads.

While the packages used for MOSFETs Q1 and Q2 may look unusual, they are actually much the same as an 8-pin SOIC package IC, but with the leads along one side joined into one larger tab. This improves heat removal, lowers resistance and also makes correctly orienting them easier.

Take care that the leads are aligned within their pads. The only real difference in soldering these compared to SOIC-8 parts is due to the greater thermal mass of the large metal tab and the copper areas on the PCB.

Moving on to inductors L1 and L2, the thermal effect will be even more apparent here. They are not polarised, but you will need a good amount of heat to complete the soldering.

It's best to lay down some flux paste on one pad, add some solder to the other pad, slide and/or press down the part into place while heating that solder, then add solder to the opposite pad. Finally, refresh the first pad you soldered.

Check that the solder fillets are joined to both the inductor and PCB pads before proceeding further.

Now clean the PCB of excess flux and thoroughly inspect all the parts for bridges and dry joints; they will be easier to see and fix after cleaning.

There are only a handful of through-hole parts remaining. You can mount fuse holders F1 and F2 by installing a fuse and slotting the whole assembly into the PCB. This ensures that the tabs are aligned correctly and spaced far enough apart to allow a fuse to be fitted. Like many of the parts, they may need more heat to let the solder take to the large copper areas.

Next, mount the terminals for CON1 and CON2, ensuring that any connected wires can exit from the board (most barrier terminals allow wires to be inserted from either side, but there are exceptions). JP1 and its jumper can then be installed near CON1. Leave the jumper in place for testing.

Finally, fit the two multi-turn trimpots, VR1 and VR2, near F2. Make sure their screws are to the left, as shown in the overlay and photos; if they are reversed, they will not operate correctly.

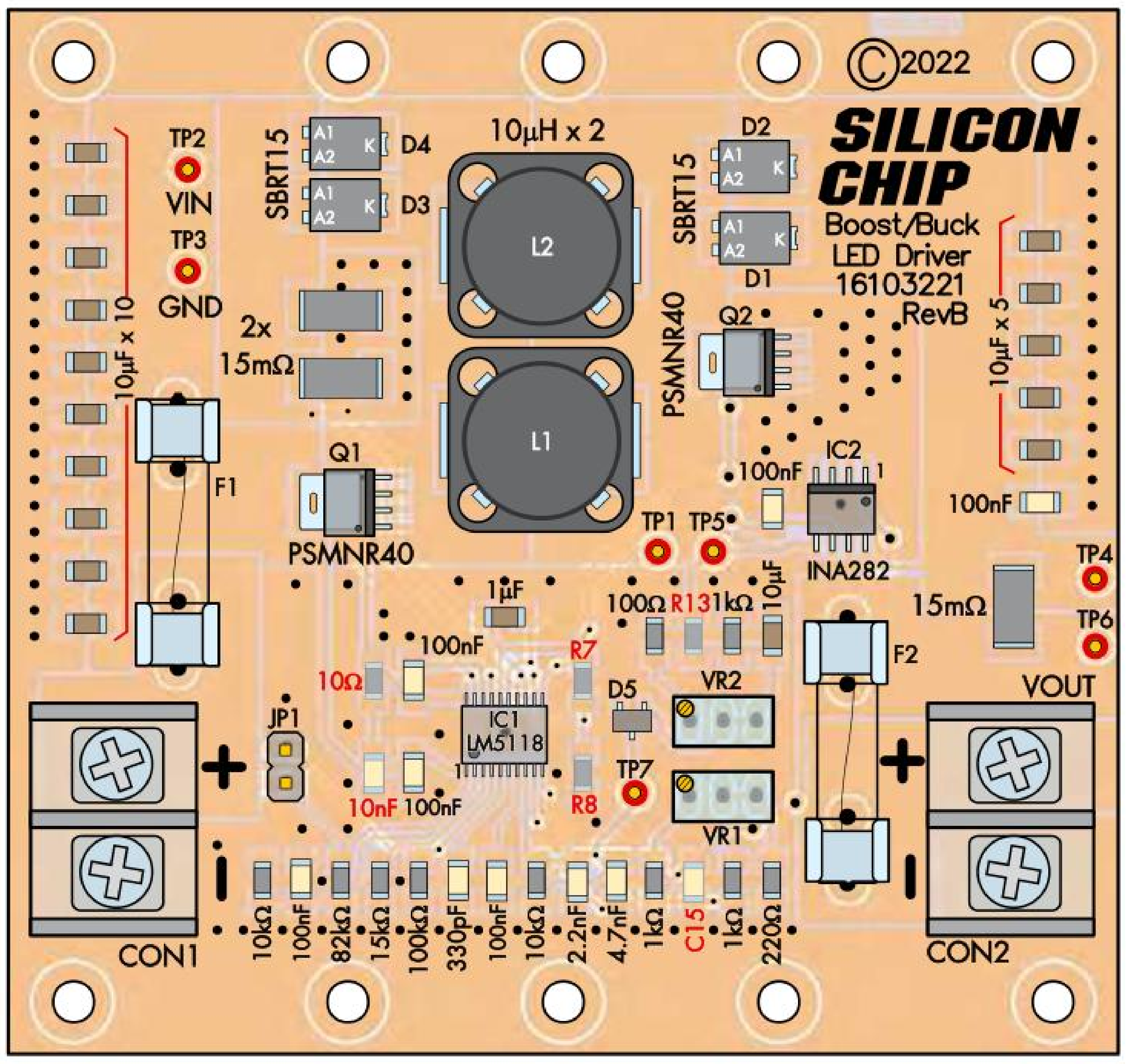


Fig.4: most of the components on the board are SMDs, but only IC1 has closely-spaced leads. Having said that, some of the other components can be somewhat challenging simply due to the combined thermal mass of those parts and the PCB copper. Most components are not polarised or only fit one way; it's mainly the ICs and trimpots that you have to be careful orienting.

Parts List – Buck-Boost LED Driver

1 double-sided PCB coded 16103221, 85mm x 80mm
2 2-way 10A barrier terminals, (CON1, CON2) **[Altronics P2101]**
1 2-way pin header, 2.54mm pitch, with jumper shunt (JP1)
2 10A 10µH SMD inductors, 14 x 14mm (L1, L2) **[SCIHP1367-100M]**
4 M205 fuse clips (F1, F2)
2 10A M205 fast-blow fuses (F1, F2)
6 M3 x 10mm tapped spacers (to mount to LED panel)
10 M3 x 6mm panhead machine screws (to mount to LED panel)
2 5kΩ 25-turn vertical top-adjust trimpots (VR1, VR2) **[Jaycar RT4648 or Altronics R2380A]**

Semiconductors
1 LM5118MH buck-boost regulator, SSOP-20 (IC1)
1 INA282AIDR current shunt monitor, SOIC-8 (IC2)
4 SBRT15U50SP5 schottky diodes, POWERDI5 package (D1-D4)
2 PSMN4R0-60YS or BUK9Y4R8-60E N-channel MOSFETs, LFPAK56/SOT669 (Q1, Q2)
1 BAT54, BAT54S or BAT54C schottky diode, SOT-23 (D5)

Capacitors *(SMD M3216/1206-size SMD X7R ceramics, 35V or higher rating)*
16 10µF
1 1µF
6 100nF
1 4.7nF
1 2.2nF
1 330pF

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Resistors *(all SMD M3216/1206-size $^{1}/_{8}$W 1% except as noted)*
1 100kΩ
1 82kΩ
1 15kΩ
2 10kΩ
3 1kΩ
1 220Ω
1 100Ω
3 15mΩ 3W M6332/2512

Ensure that they are both wound to their minimums by turning their adjustment screws anti-clockwise by 25 turns or until you hear a clicking indicating that they have reached the end of their travel.

There are seven test points on the board, but you do not need to fit PC pins; you can simply probe them with a standard set of DMM test leads.

Testing

You will need fuses installed for testing, but since initial testing is done with a multimeter, you can fit lower-rated (eg, 1A) fuses if you have them on hand. If you have a current-limited PSU, you can use that too.

Connect a voltmeter across CON2 and apply a power source of around 12V DC (above 11.5V) to CON1. You should see about 6.6-7.0V at CON2. If you get a reading near the supply voltage instead, you could have a short circuit somewhere. In that case, switch off and check the PCB for faults before proceeding.

Slowly turn VR1's screw clockwise. After the trimpot's mechanism re-engages, you should see the voltage on CON2 increase, rising to nearly 35V at its maximum setting. If so, wind it back down around 11V. If you can't adjust the output voltage correctly, switch off and check for faults.

If you have used low-value fuses, change these now to your nominal value; for the LED panels we described earlier, 10A each is a good choice.

You can also test that the current limiting works if you have a suitable load such as a power resistor or test load (like the one described starting on page 16 of this issue). The minimum current limit when VR2 is set fully anti-clockwise is around 1.8A.

You can easily monitor the output current at TP5 (near IC2) relative to TP3 (ground, at top left). This is the raw output from IC2, and it gives 0.75V per amp. So 1.5V at TP5 corresponds to 2A.

Also, you can monitor the output voltage at TP6 (near CON2) relative to ground.

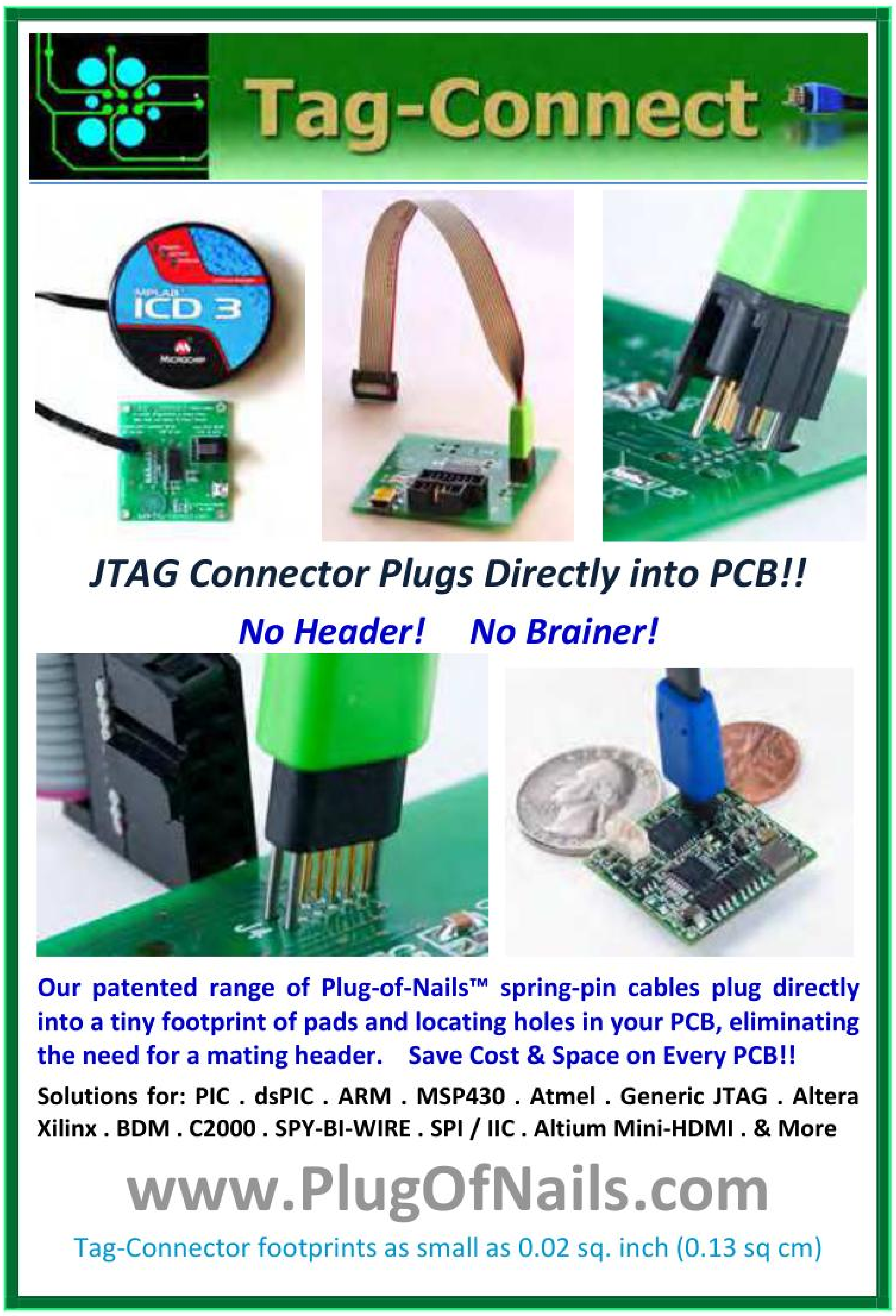
Adjust your load until the current limiting kicks in. Reducing the load resistance should let the output voltage drop while the current stays mostly constant.

LED panel mounting

The *Driver* is designed to mount on the back of the LED panel using the mounting holes near the power terminals, so you can use short flying leads to connect from CON2 to the panel's inputs.

While your iron is on, you can connect some leads to the LED panels. As you will know by now, soldering inductors L1 and L2 to the PCB requires much heat, but nowhere near as much as is needed for soldering to the aluminium-cored PCB that forms the LED panel.

You might even find that you need to preheat the panels with a hot air rework tool or similar before you can successfully solder those leads. We also suggest that you pre-tin the leads and have a generous amount of solder on the iron's tip (to accumulate some thermal mass).



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To set up the *Driver* to work with LED panels, disconnect all loads, set the output voltage to around 13V and adjust the current limit fully anti-clockwise to 2A. The 13V setting is simply a failsafe in case the current limiting stops working.

Keep in mind that the LED panels are very bright; even at 2A, it will likely be too bright to look at. We rested them on their edge during testing to aim them away from our faces.

If you then connect the LED panel and power up the *Driver*, you should see the output voltage drop to approximately 12V as the *Driver* switches over to its current-limited mode.

If you don't see the voltage drop, the current limiting may not be working. In that case, measure the voltage at TP7 neat VR1. This feedback voltage should always be around 1.23V when the *Driver* is operating correctly.

Check that there is a slightly higher voltage at D5's top right (anode) terminal; this means that the diode is feeding current into TP7 and controlling the output. If this is more than around 0.3V higher, D5 may be the wrong type or not injecting current correctly.

If all is well, you can then permanently wire up CON2 to the LED panel and mount the *Driver* using tapped spacers. Use four tapped spacers with a screw at each end to mount the Driver PCB to the LED panel at its mounting holes.

Then use two further tapped spacers mounted to the PCB only as standoffs to keep the PCB from moving, flexing and shorting against the aluminium back of the LED panel. See our photos for details of this arrangement.

Adjust VR2 to provide a suitable current and thus brightness. If you get much above 5A, you might find that the current limiting no longer dominates, and the VR1 voltage setting may need to be increased above 13V.

Keep in mind that both the *Driver* and LED panel will get quite warm during use, so they should be mounted to allow free air circulation.

Suppose you see the LED panel rapidly flickering during operation. In that case, the supply voltage is probably dropping below the UVLO threshold, causing the *Driver* to cut out and then switch back on when the input voltage recovers. Check your supply and that the connections to CON1 do not have too much resistance.

Driving two panels

We briefly experimented with running two panels in series, as this is the easiest way to guarantee they operate at the same current. The main difference is that the voltage needs to be set to around 26V.

This certainly seems to work fine, but the *Driver* is likely to be less efficient in this mode unless the input voltage is raised to about 24V.

You can change the UVLO threshold to suit a 24V battery by changing the 82kΩ resistor to 160kΩ, and 10kΩ resistor to 9.1kΩ. This will set the threshold to approximately 22.8V.

As noted in the *Features* panel, you can also use the *Driver* as a DC-powered battery charger, a 24V-to-12V converter, or a 12V-to-24V converter for many different applications.

For the 24V-to-12V arrangement, the output limit can be set up to 8A, with a 10A fuse at F2, but with F1 reduced to 5A. In this case, you would also change the 82kΩ resistor to 180kΩ.

For a 12V-to-24V arrangement, F1 should be 10A and F2 should be 5A, with an appropriate current limit near 5A set using VR2.

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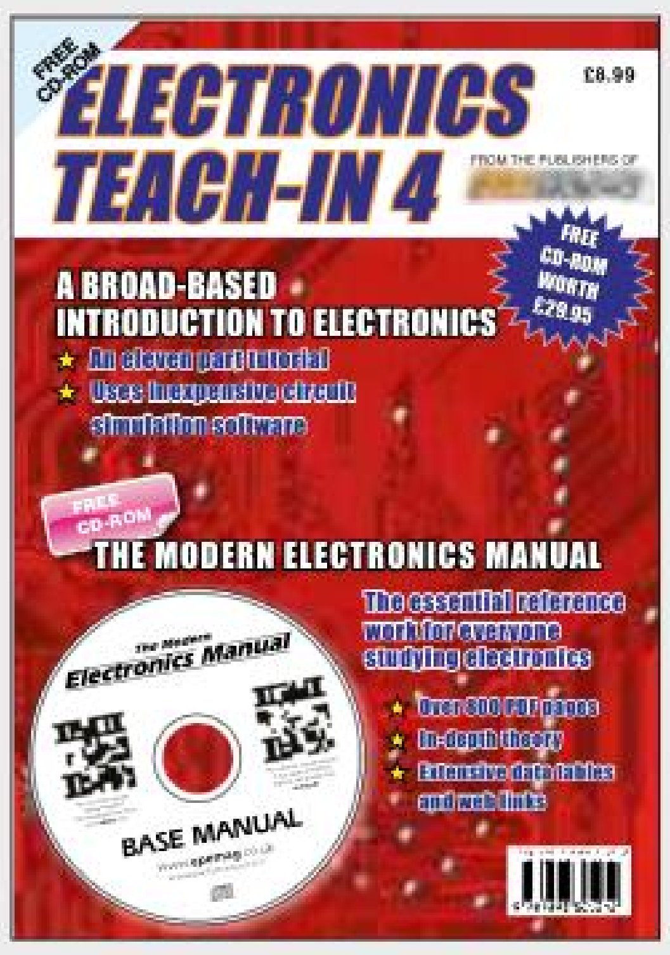
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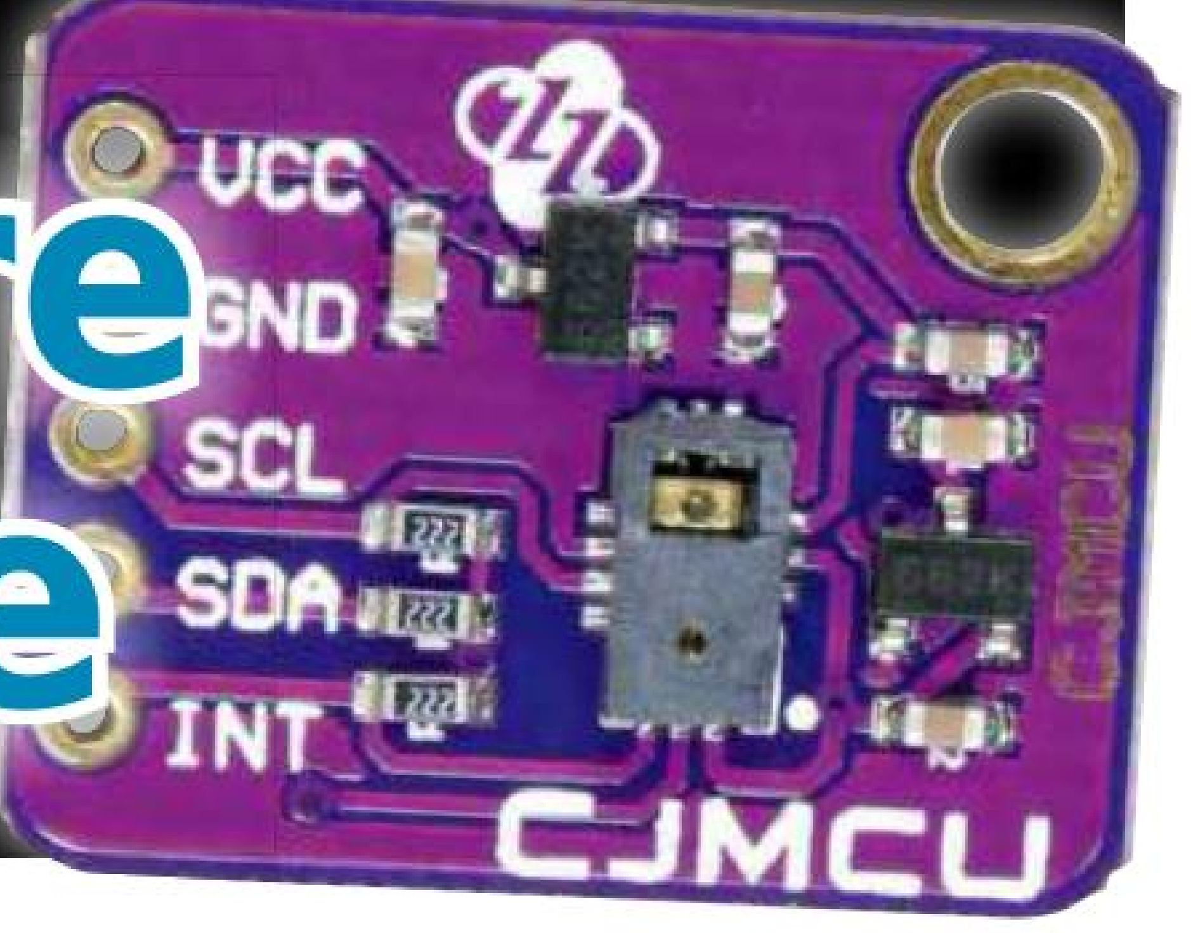
Using Cheap Asian Electronic Modules

By Jim Rowe

CJMCU-7620 Gesture Recognition Module


VCC
GND
SCL
SDA
INT
CJMCU

With this module, you can experiment with sensing and recognising gestures made with your hands. It is very small, relatively low in cost and can easily be hooked up to an Arduino or a Micromite. There are some tricks to make it work, detailed in this article.

When I first saw this little module advertised, I confess I was a bit dubious. How could a 16 x 20mm module selling for as little as £5-10 be capable of sensing and recognising a range of hand gestures? I was intrigued enough to order a couple, to see if the claims were justified.

Gestures it is said to recognise include moving a hand left, right, up, down, forward or back, clockwise or anti-clockwise, and waving.

While I ordered my modules from Banggood (China), it is often well worth shopping around (eBay/Amazon) to see if you can order locally for much speedier but probably pricier delivery.

When my modules arrived, I found they were based on an SMD 'micro-module' called the PAJ7620U2, which is made by PixArt Imaging Inc based in Hsinchu, Taiwan: **www.pixart.com**

The PAJ7620U2 itself measures only 5.2 x 3 x 1.88mm but is surprisingly complex, as seen from the internal block diagram, Fig.1.

Sensing is done using pulses of infrared (940nm) light from the IR LED shown at upper left, with reflected light detected by a 30 x 30 pixel IR sensor array at centre left. The gesture sensing range of the PAJ7620U2 is specified as being 100-200mm within a 60° cone.

The rest of the circuitry is involved in timing the LED pulses and the sensor array scanning, extracting information from the sensor array, recognising any detected gesture and saving the data in a memory register bank.

There are also two serial interfaces: an I^2C interface used mainly for interfacing the PAJ7620U2 with a microcontroller unit (MCU) for gesture recognition, and an SPI interface primarily intended for the PAJ7620U2's other mode of operation, 'cursor' mode.

Cursor mode provides real-time data output describing the position, size and brightness of an object within the range of its IR sensor array.

Fig.2 shows the small number of extra components around the PAJ7620U2 in the CJMCU-7620 module. Apart from the PAJ7620U2 (IC1), it has just two tiny 3.3V low-dropout (LDO) voltage regulators, REG1 and REG2, with their associated capacitors, used to supply the logic part of IC1 (REG1) and the IR LED (REG2).

Then there are three 2.2kΩ resistors to pull up the SDA, SCL and INT outputs of IC1 to the positive supply rail. That's it!

The CJMCU7620 module does not provide connections to the SPI interface of IC1, only to the I^2C interface, meaning it probably isn't suitable for use in cursor mode.

All the I^2C interface connections are brought out to the 5-pin header at lower left in Fig.2.

Figuring out how to use it

Before trying it out, I looked around on the internet to see if I could find a data sheet or application information

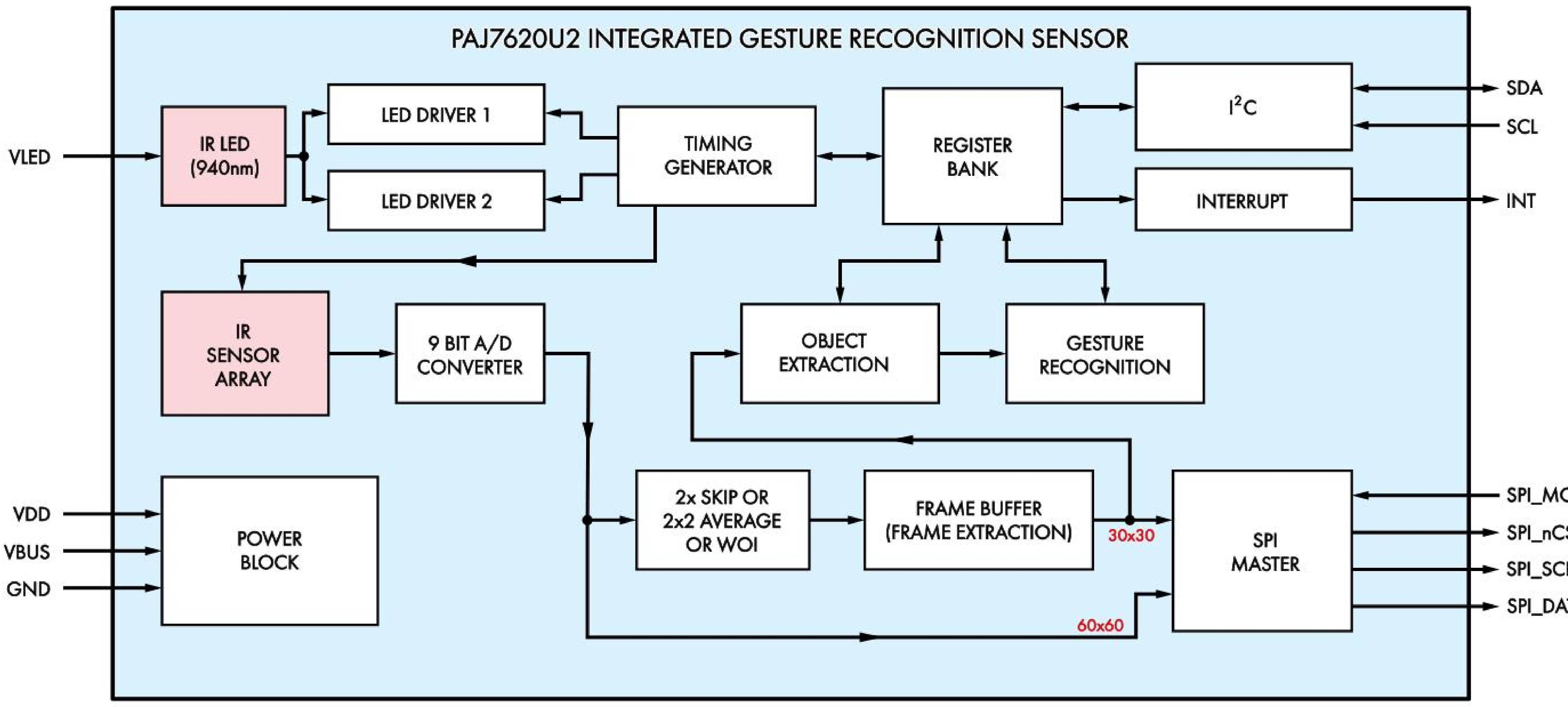
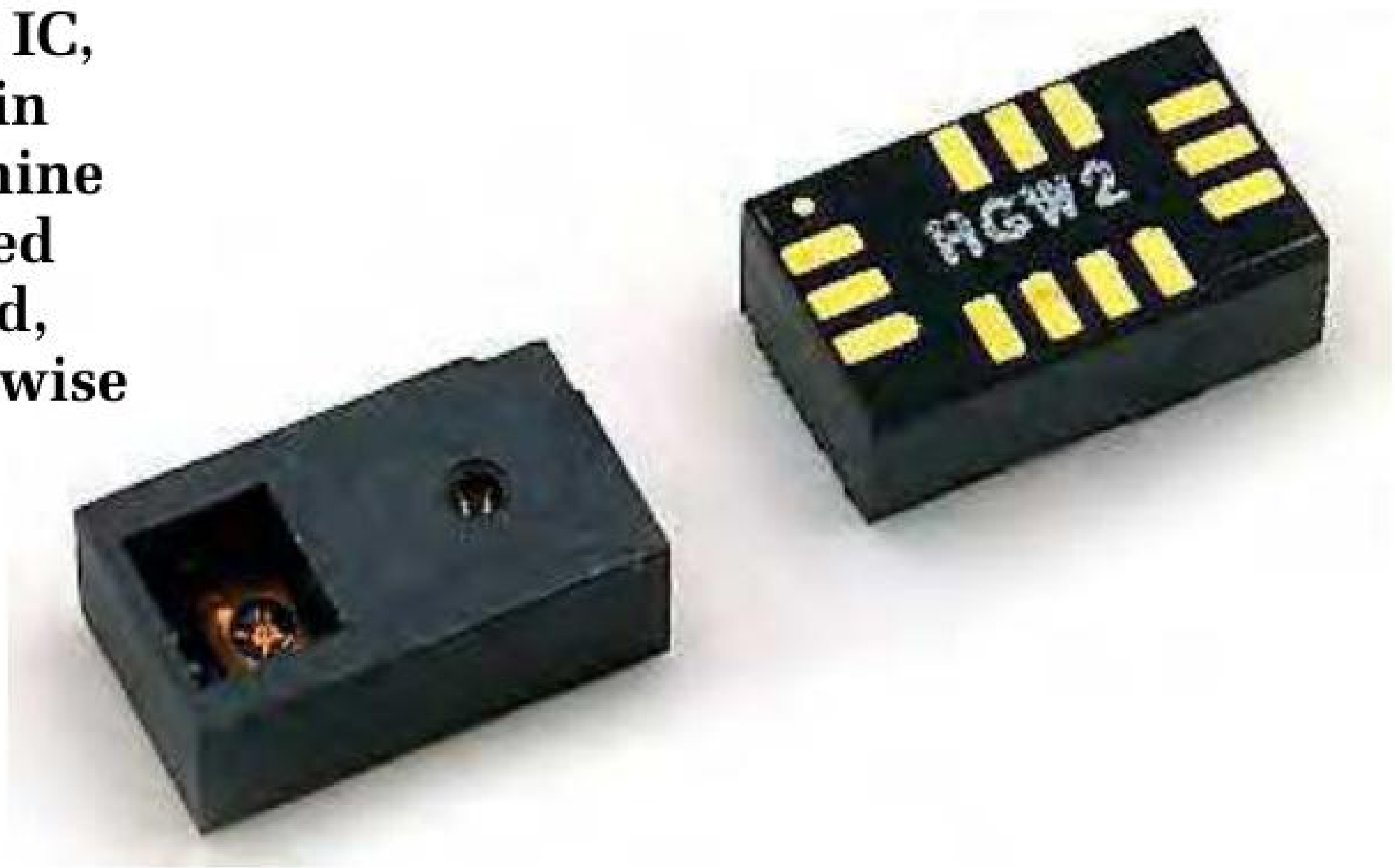

PAJ7620U2 INTEGRATED GESTURE RECOGNITION SENSOR
VLED
IR LED (940nm)
LED DRIVER 1
LED DRIVER 2
TIMING GENERATOR
REGISTER BANK
I²C
INTERRUPT
SDA
SCL
INT
IR SENSOR ARRAY
9 BIT A/D CONVERTER
OBJECT EXTRACTION
GESTURE RECOGNITION
VDD
VBUS
GND
POWER BLOCK
2x SKIP OR 2x2 AVERAGE OR WOI
FRAME BUFFER (FRAME EXTRACTION)
30x30
60x60
SPI MASTER
SPI_MCLK
SPI_nCS
SPI_SCK
SPI_DATA

Fig.1: the block diagram for the PAJ7620 gesture recognition sensor IC. The module's detection range for gestures using this IC is 5 to 15cm, with it typically processing an image size of 30x30 pixels. The datasheet can be found at: https://bit.ly/pe-jun23-paj

An enlarged shot of the PAJ7620 IC, which the CJMCU-7620 module in the lead photo is based on. The nine basic gestures that can be detected are: right, left, up, down, forward, backward, clockwise, anti-clockwise and waving.



on the PAJ7620U2. Although I did manage to find a data sheet (actually, two different data sheets, one of which was more complete than the other), I couldn't find much in the way of application information. And neither version of the data sheet was all that helpful either.

One of them, titled *PAJ7620U2 General data sheet*, gives you a fair bit of information, including the pin configuration, main electrical specifications and a set of tables showing the two banks of 256 memory registers. But these tables contain only brief and somewhat cryptic descriptions of the function of most of the registers.

There was no information in that data sheet about the PAJ7620's serial interfaces. For that, you must refer to the second data sheet titled, *PAJ7620U2 Product data sheet*, which contains details of the device's I^{2}C and SPI interface protocols and timing parameters.

Neither data sheet gives much information on things like what data needs to be written to which registers to initialise the PAJ7620U2 for gesture recognition, the exact order in which the data should be written, or the correct timing for this writing.

There is also no real information on decoding the recognised gesture data, apart from a table showing which of the eight bits in register 0x43 of Bank0 indicates the gesture recognised.

So instead, I started looking for code to interface the PAJ7620U2 with an Arduino MCU, which proved much more successful. Several people had already solved most of the problems regarding communicating with the PAJ7620U2, so I was able to download a couple of Arduino sketches for communicating with the device, including two different Arduino libraries.

Analysing the libraries and sketches provided much more insight into how to initialise the PAJ7620U2 and then use it for gesture recognition. But I still ran into significant problems when I tried writing a Micromite program to initialise the PAJ7620U2 and decode its gestures. But more about that later; let's start by looking at the situation with an Arduino.

Using it with an Arduino

Hooking the module up to an Arduino is very straightforward, as you can see from Fig.3. The module's V_{CC} pin connects to the Arduino's +5V pin, its GND to one of the Arduino's GND pins, its SDA pin to the Arduino's A4 pin and its SCL pin to the Arduino's A5 pin. The module's INT pin is left unconnected as it is not required.

As for the software, first, you need to download one of the Arduino PAJ7620U2 libraries. You'll find two of these on the main Arduino website at: **www.arduino.cc/en/libraries/**

One is written by Seeed Studio, called 'Gesture-paj7620', and the other is written by multiple authors and is called 'RevEng-PAJ7620'. Both of them can also be found on GitHub:

https://bit.ly/pe-jun23-seeed
https://bit.ly/pe-jun23-reveng

These GitHub links are probably the most helpful because they provide quite a bit of documentation. Both libraries also come with example sketches to get you up and running.

When you have downloaded one or the other of these libraries (they both come as a ZIP file), save it in a convenient folder and then start up your Arduino IDE (integrated development environment). If you haven't installed the IDE yet, you can always download the latest version from: **www.arduino.cc/en/software**

Now you can install the downloaded library in the IDE by clicking on the top drop-down 'Sketch' menu button, clicking on 'Include Library' and then 'Add .ZIP Library'. You can then direct the IDE to the library ZIP file you saved earlier, and it will install the library (and its example sketches) without further ado.

Next, click on the top drop-down 'File' menu, go down to 'Examples', select 'Examples from Custom Libraries' and then choose the library you've just installed (Gesture PAJ7620 or RevEng PAJ7620). You can then select one of the example sketches that came with it. It will then open up that sketch in the IDE window for you to look over and upload.

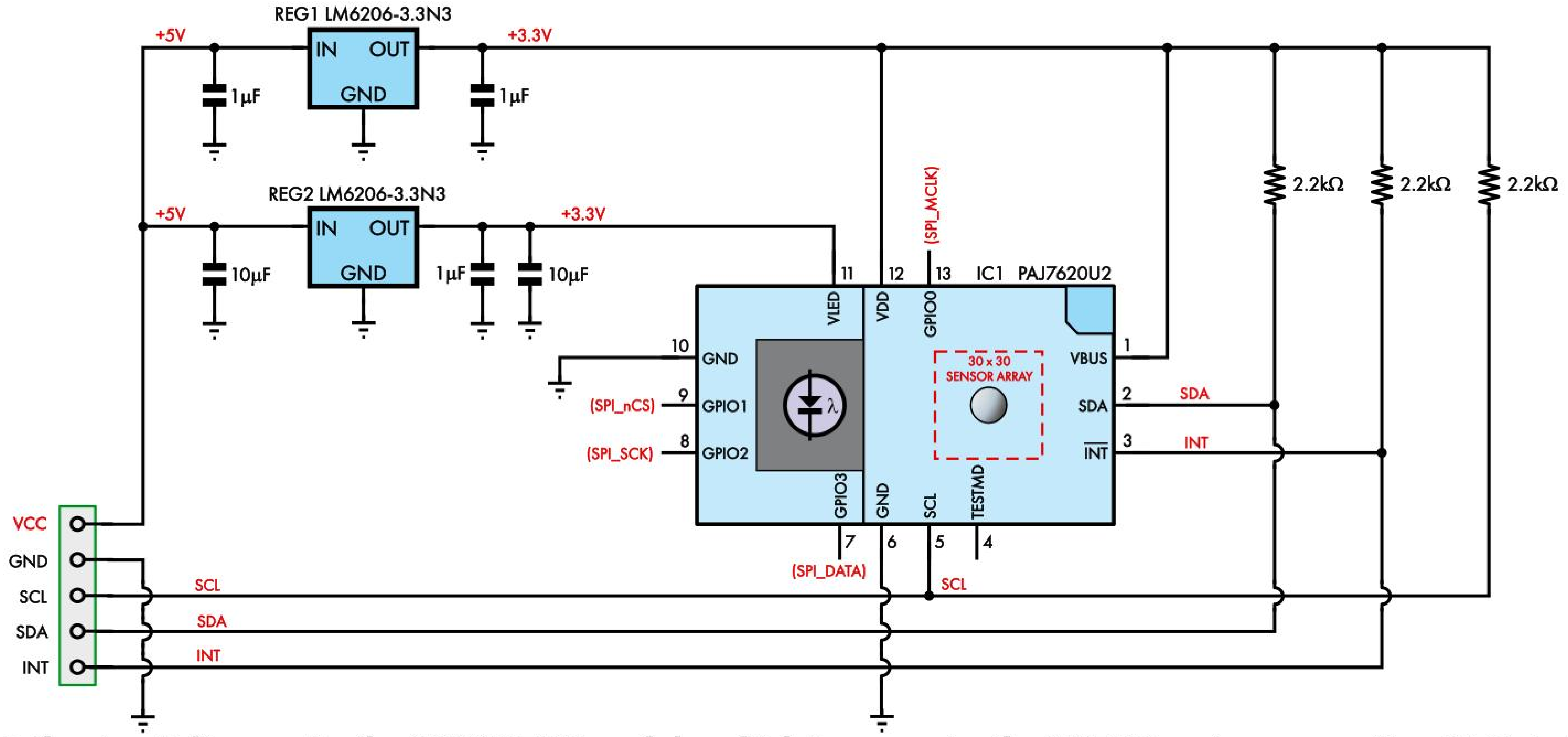


Fig.2: the circuit diagram for the CJMCU-7620 module, which incorporates the PAJ7620 gesture recognition IC. Data is read via an I^{2}C bus; while the chip has an SPI interface, these pins are not connected on this module.

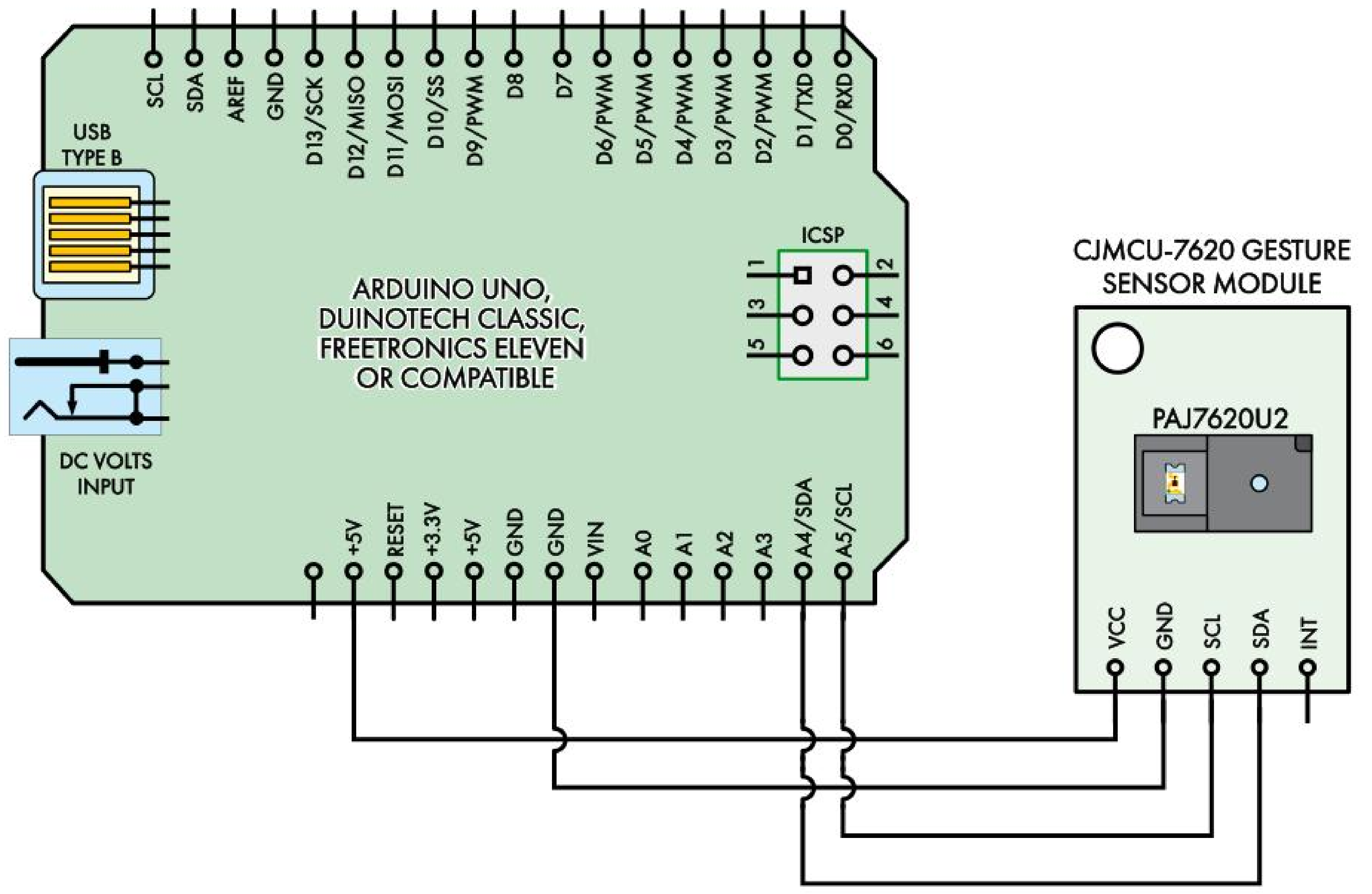

SCL
SDA
AREF
GND
D13/SCK
D12/MISO
D11/MOSI
D10/SS
D9/PWM
D8
D7
D6/PWM
D5/PWM
D4/PWM
D3/PWM
D2/PWM
D1/TXD
D0/RXD
USB TYPE B
ICSP
1
2
3
4
5
6
ARDUINO UNO, DUINOTECH CLASSIC, FREETRONICS ELEVEN OR COMPATIBLE
DC VOLTS INPUT
+5V
RESET
+3.3V
+5V
GND
GND
VIN
A0
A1
A2
A3
A4/SDA
A5/SCL
CJMCU-7620 GESTURE SENSOR MODULE
PAJ7620U2
VCC
GND
SCL
SDA
INT

Fig.3: when running our sample Arduino sketch, follow this wiring diagram to connect the sensor module to an Arduino or equivalent device.

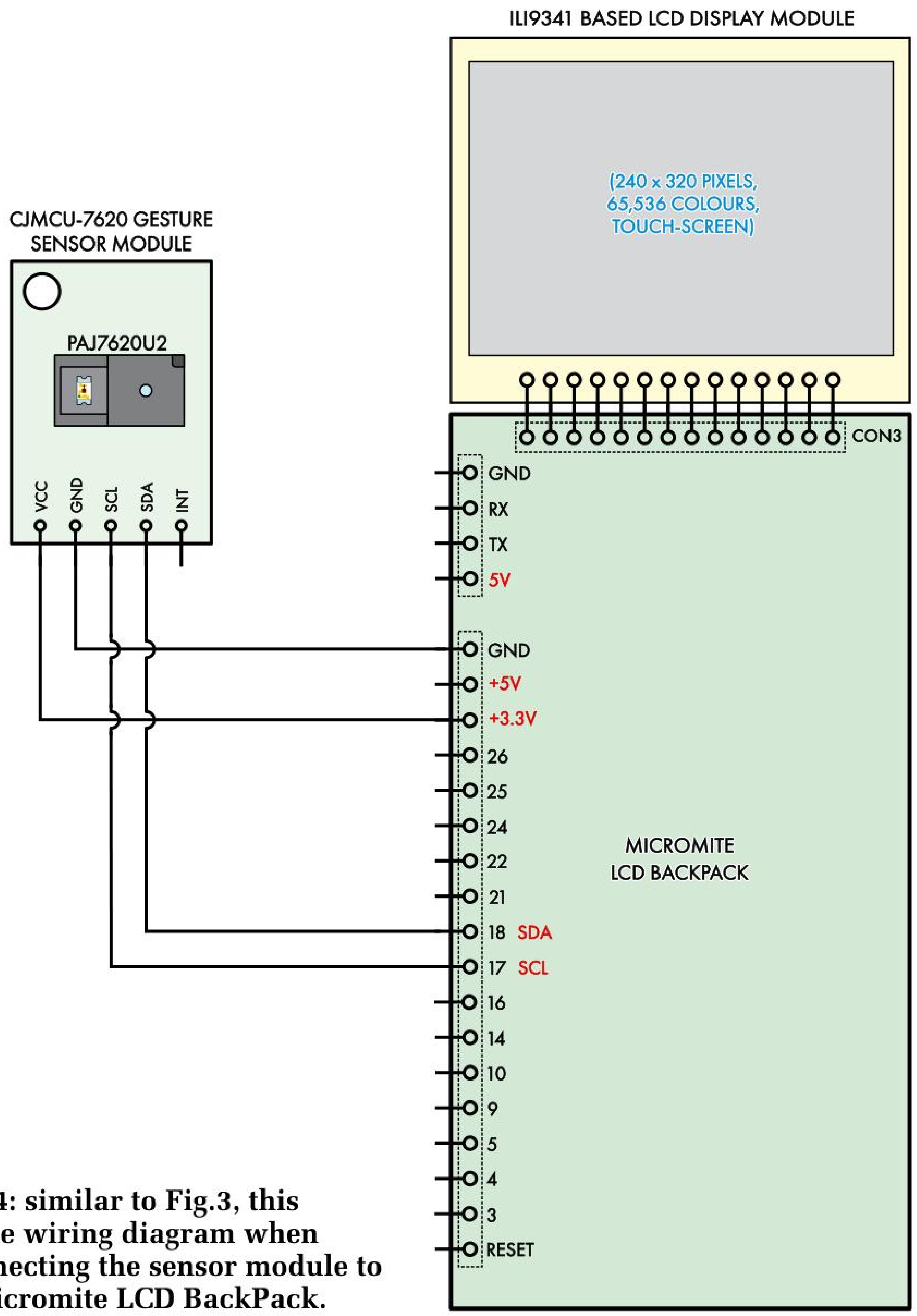

ILI9341 BASED LCD DISPLAY MODULE
(240 x 320 PIXELS, 65,536 COLOURS, TOUCH-SCREEN)
CON3
CJMCU-7620 GESTURE SENSOR MODULE
PAJ7620U2
VCC
GND
SCL
SDA
INT
GND
RX
TX
5V
GND
+5V
+3.3V
26
25
24
22
21
18 SDA
17 SCL
16
14
10
9
5
4
3
RESET
MICROMITE LCD BACKPACK

Fig.4: similar to Fig.3, this is the wiring diagram when connecting the sensor module to a Micromite LCD BackPack.

Before you can run the sketch, you will need to connect the CJMCU-7620 module to an Arduino, as shown in Fig.3, then plug the Arduino into one of your computer's USB ports.

Then you should check in the Windows Control Panel or Settings dialog box to make sure that the Arduino has connected properly, and find the virtual serial port it has been allocated. In most cases, this will be something like 'Arduino Uno (COM4)'.

Next, click on the Arduino IDE Tools menu and you should find your Arduino and its port, shown something like this:

```
Board: "Arduino Uno"
Port: "COM4 (Arduino Uno)"
```

If all seems well, go to Tools → Serial Monitor. This will display a second window so that you can monitor messages sent back from the Arduino. Set the Serial Monitor for 9600 baud since most Arduino sketches use that speed.

Then, assuming you have already loaded the example sketch, it's simply a matter of clicking on Sketch → Verify/Compile. If no problems arise, use Sketch → Upload to direct the IDE to send the compiled sketch to your Arduino. Once that finishes, moving your hand in front of the CJMCU-7620 module should result in messages appearing in the Serial Monitor.

Note that the CJMCU-7620 module should be oriented so that its five header pins are at the bottom, as shown in Fig.3. This will have the PAJ7620U2 device with its IR LED to the left and the lens in front of its IR sensor array to the right. That is the device orientation assumed by the sketches; other orientations will tend to give recognition errors, like 'Up' or 'Down' instead of 'Right' or 'Left'.

If you want to orient the module differently later, the sketch or its libraries can be revised to suit the new orientation.

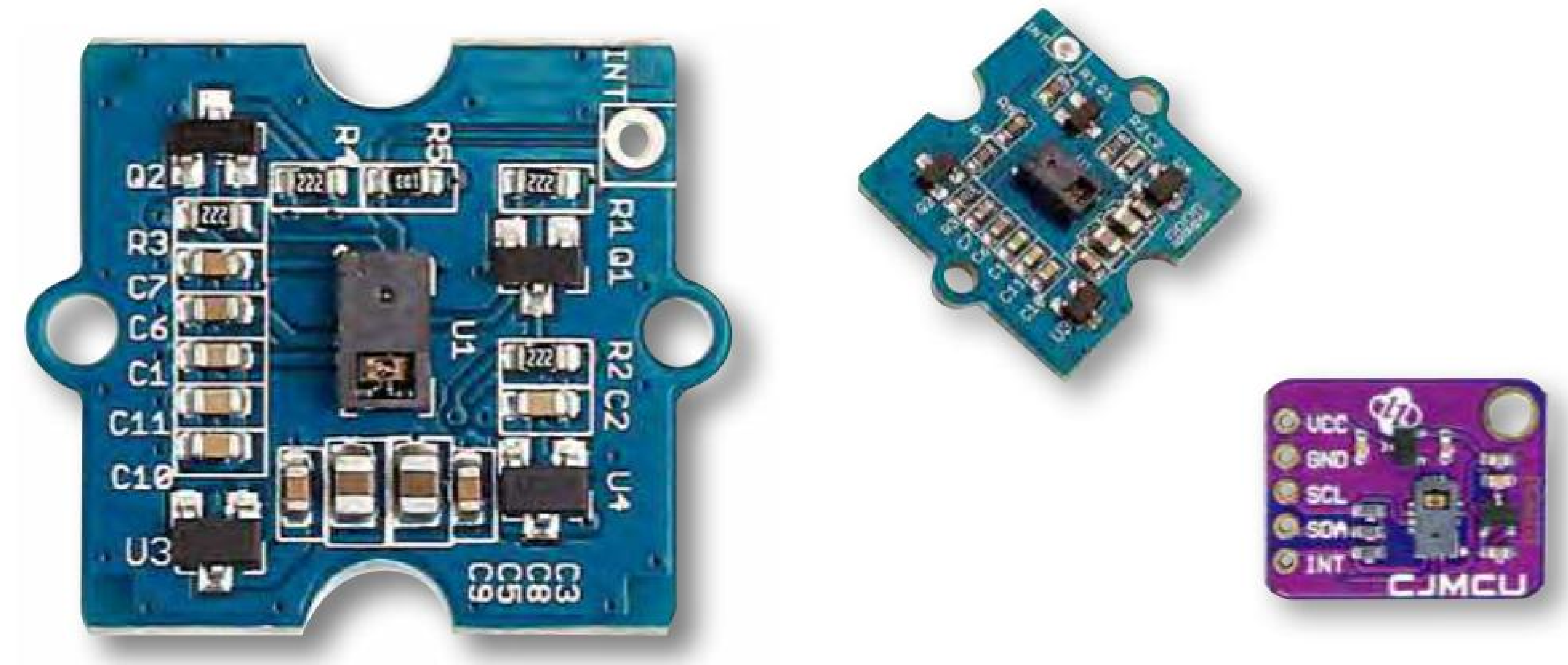
So hooking up the CJMCU-7620 module up to an Arduino and using that combination is pretty straightforward. Now let us look at what's involved in using it with a Micromite.

Using it with a Micromite

First, the easy part: connecting the module to a Micromite. As shown in Fig.4, this is much the same as with an Arduino, with one small difference. The SDA and SCL lines connect to pin 18 (SDA) and pin 17 (SCL) of the Micromite and the GND line to the Micromite's GND pin as you'd expect, but the module's V_{CC} pin connects to the Micromite's +3.3V pin, *not* the +5V pin.

This looks wrong, considering that the module's circuit in Fig.2 shows that it has its own pair of LDO voltage regulators onboard to provide the PAJ7620U2 with two regulated +3.3V supplies. So connecting the module to a +3.3V supply would seem both unnecessary and likely to prevent the onboard regulators from doing their job.

But the fact is, we found the module gave much more reliable and consistent results when it was powered from the Micromite's +3.3V line, not the +5V line. It's not easy to explain or understand, but it did seem to work better that way!



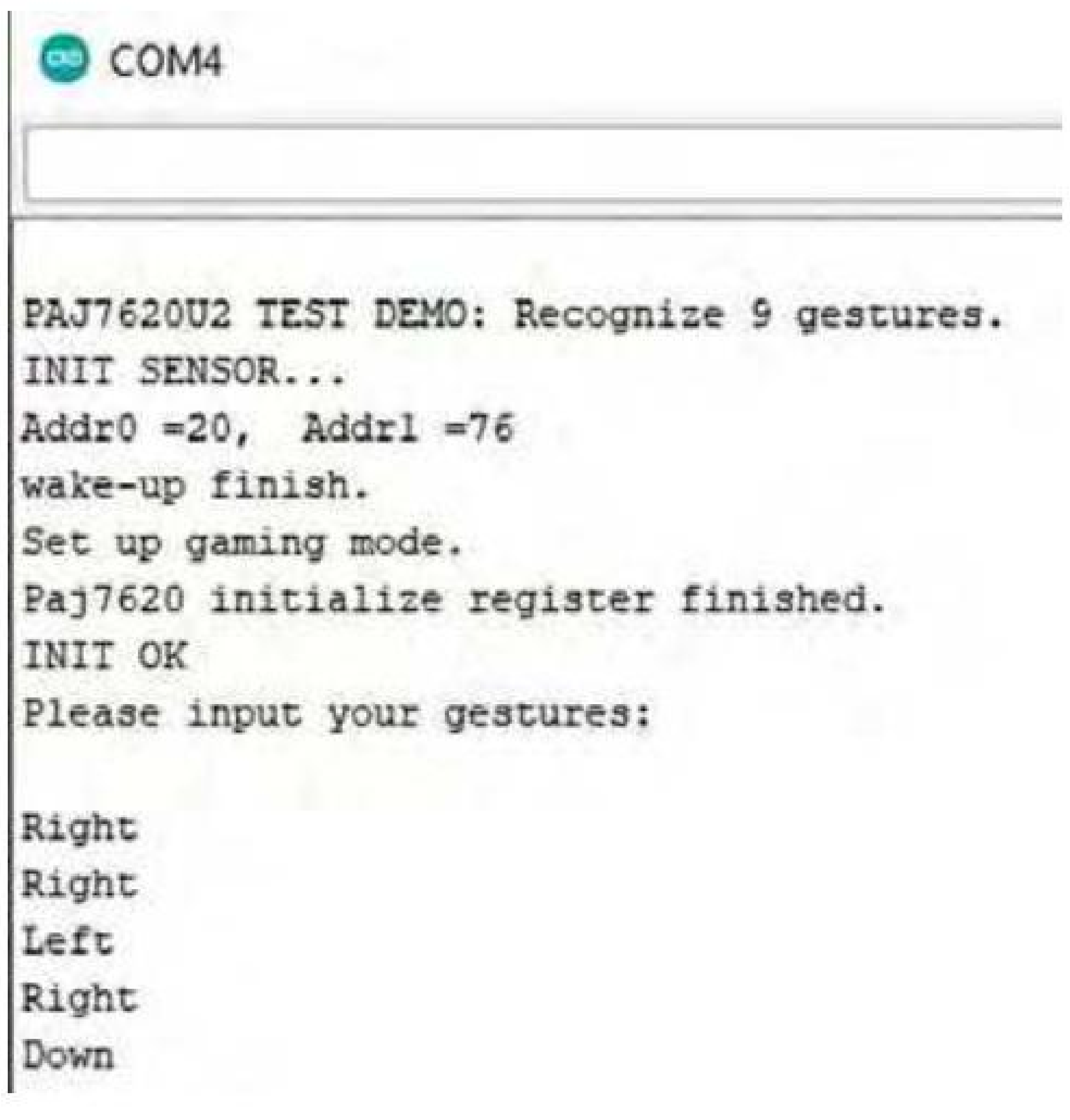
Seeed Studios sells an alternative, slightly larger sensor module that can be purchased from: https://bit.ly/pe-jun23-grove – both the original (lower right) and alternative (top) are shown above at actual size.

The next difficulty is the software. I couldn't find any pre-existing MMBasic code for the PAJ7620U2, so I had to write it myself. Since the PixArt data sheets were so unhelpful, I had to spend quite a bit of time studying the Arduino libraries and sketches to see how they worked.

It doesn't seem too difficult. First, you check for the presence of a PAJ7620 and confirm that it is functional, then send over 200 bytes of initialising data to specific memory registers to set it up correctly in gesture recognition mode. Finally, you keep polling one of its memory registers (Bank0, address 0x43) to read its gesture recognition codes.

Taking this approach ended up with a program that seemed to work pretty well, at least from time to time. When I made various gestures in front of the PAJ7620U2 device, the Micromite would correctly identify the gesture on its LCD screen and send the same information back to the MMEdit Chat window.

But this would only happen some of the time. At other times, the setup seemed only to recognise one gesture (like 'Right' or 'Down') or else become totally 'blind' and be unable to recognise any gestures at all.



```
PAJ7620U2 TEST DEMO: Recognize 9 gestures.
INIT SENSOR...
Addr0 =20,  Addr1 =76
wake-up finish.
Set up gaming mode.
Paj7620 initialize register finished.
INIT OK
Please input your gestures:

Right
Right
Left
Right
Down
```

Some sample output from the Arduino running our test program.

Tim Blythman helped me track this down to the power supply connections; after changing to using the +3.3V Micromite supply rail as described above, it started working much more reliably.

He also pointed out that I should add an extra write to a register (Bank1, register 0x65, data byte 0x12) at the end of the initialisation sequence, which made another improvement.

So we ended up with a Micromite program that is at least as accurate and reliable as either of the Arduino sketches. The program is called **PAJ7620 Gesture Rec.bas** and you can download it from the June 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**.

While functional, this program could probably use some tweaking, so if you feel you have improved it, please send us your version so we can share it with other readers.

Final comments

While writing this article, I learned that Seeed Studio offers a PAJ7620-based Hand Gesture module in their 'Grove' series of modules. This module is slightly larger (at 20 x 20mm) than the CJMCU and similar modules. It appears to have additional circuitry, including a pair of small P-channel MOSFETs to perform level translation on the SDA and SCL output lines.

It's possible that this module would give more reliable gesture recognition when used with our program running on a Micromite, even when running from the Micromite's +5V supply line, but we haven't had a chance to get one and try it out yet.

You can find documentation for this module on Seed Studio's website at: **https://bit.ly/pe-jun23-seeed2**

They also have a library and example Arduino code for their module at: **https://bit.ly/pe-jun23-seeed**

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 6

In this month's column we are going to be leaping from topic to topic with the agility of young mountain goats, so readers are encouraged to dress appropriately and responsibly. As one example, we are going to use a passive piezoelectric buzzer to super-size the 'click' sounds that occur when we press our momentary pushbutton switches, but first…

Mum knows best!

When I was 16, my mother told me it would be a really good idea for me to learn to type. She also suggested I learn Pitman shorthand. This was after she'd finished touring the world as the personal assistant to a captain of British industry. As a follow-up act, she became a principal lecturer at college teaching shorthand, typing, and business studies in English, French, and German (she never liked to restrict herself unduly).

Unfortunately, this was 1973, when the widespread proliferation of computers at home and in the office was still naught but a pipedream. At that time, I was debating whether to apply to art college or embark on a career in engineering. I never envisioned I would end up as an engineer who spends his days interviewing industry luminaries (wishing I knew shorthand) and writing books, technical articles and whitepapers (wishing I could type).

To this day, I remain a two-fingered hunt-and-peck typist. Occasionally, I see someone who can really type at speed using all ten fingers (including thumbs) to full advantage, and I think, 'I wish I'd listened to my mum.' Invariably, my mind will then meander onto other topics, such as wondering if we could type faster were we to have six, seven or even eight fingers on each hand.

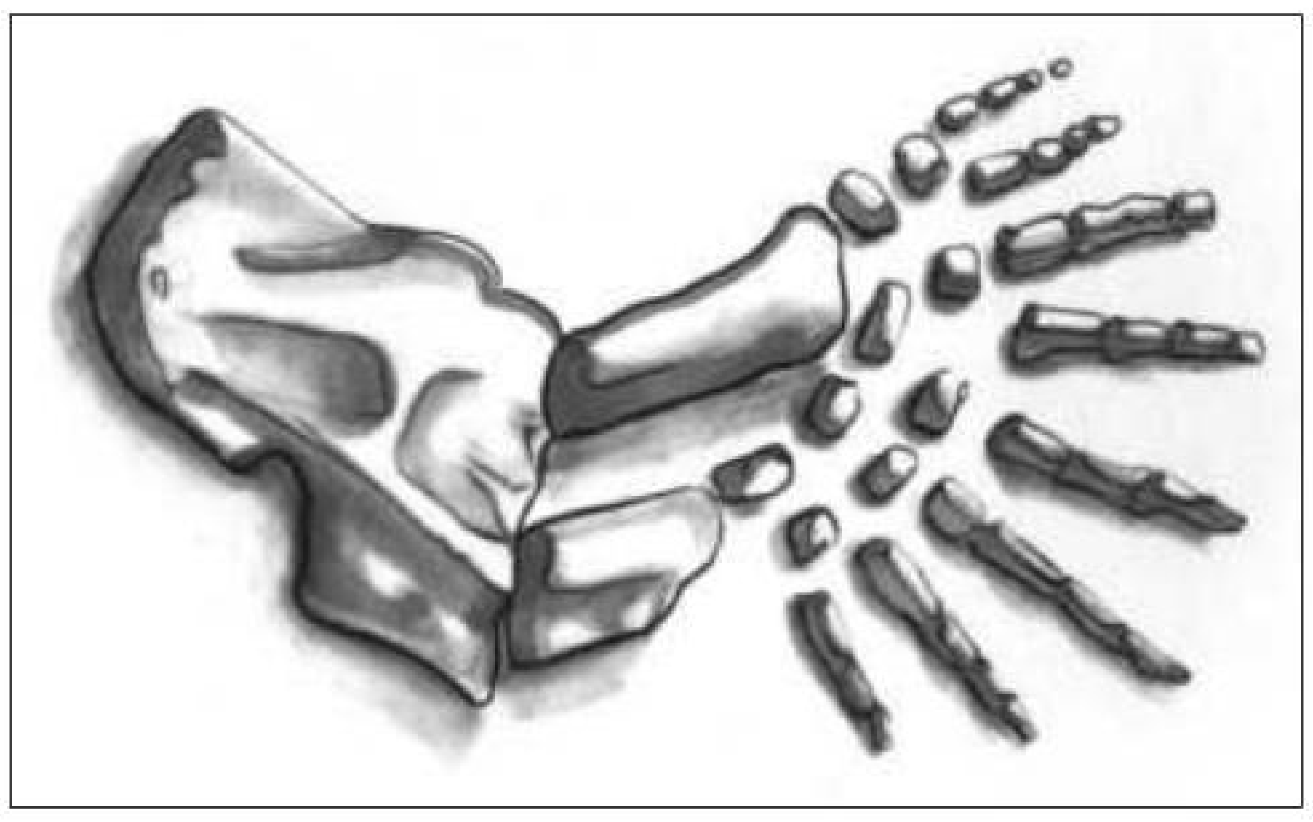
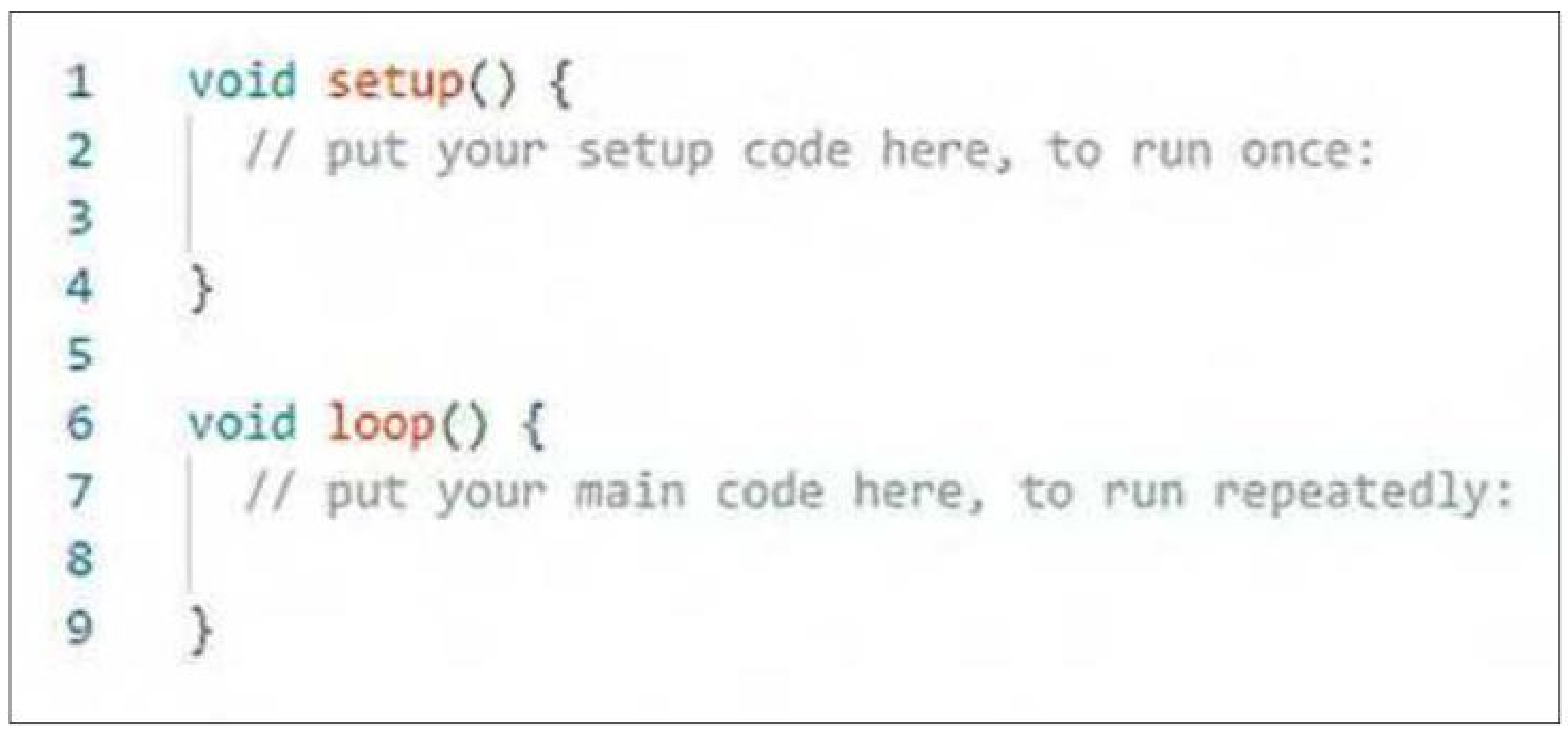


Fig.1. Acanthostega had eight fingers on each hand.



```
void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Listing 1. Why once and why repeatedly?

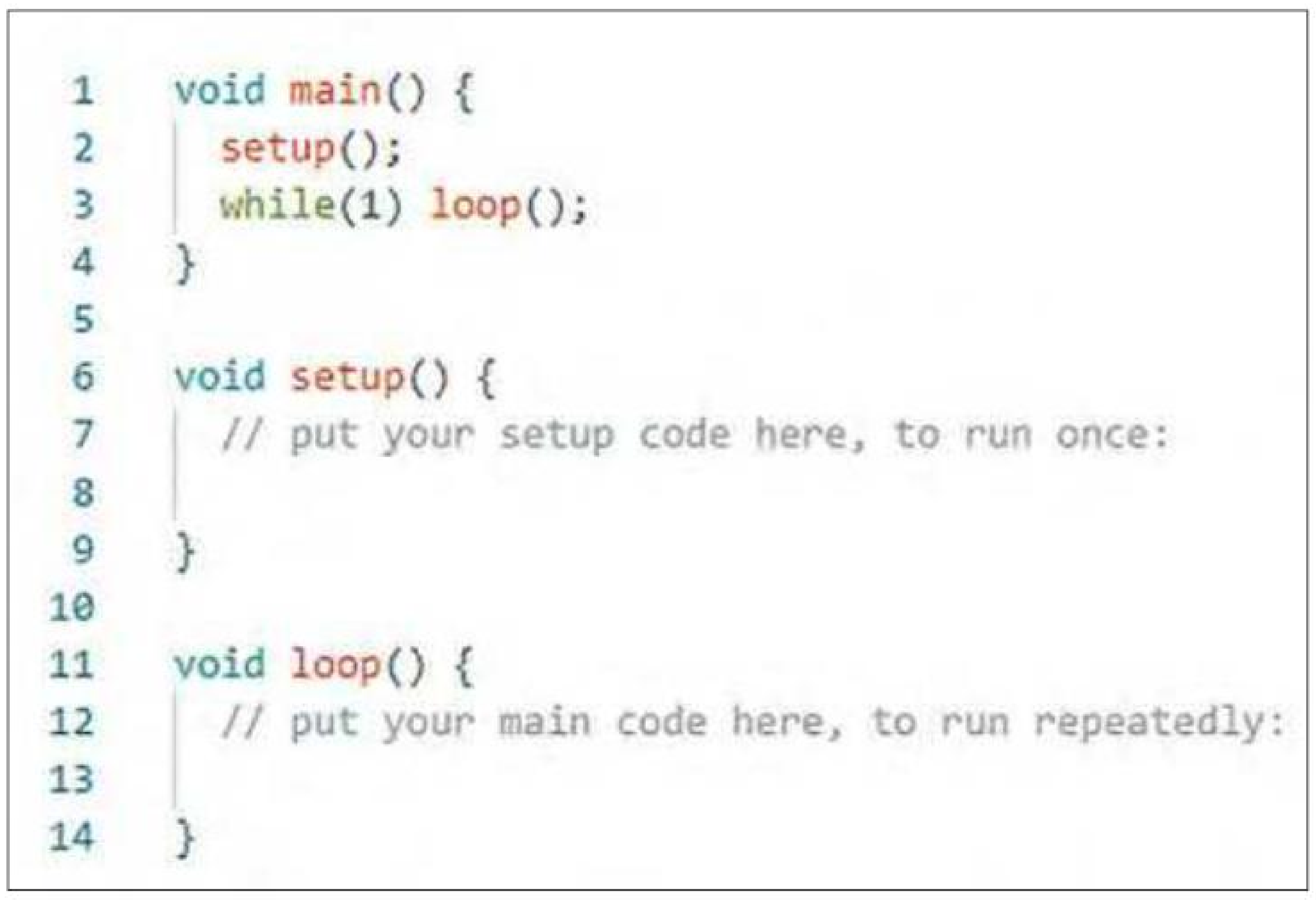
You may be raising a quizzical eyebrow at this point in the proceedings, but this isn't as far-fetched as it may seem. As I wrote in my book *Bebop Bytes Back* (yet another 850+ page tome typed with two fingers), the term 'tetrapod' refers to an animal that has four limbs, along with hips and shoulders and fingers and toes. In the mid-1980s, paleontologists discovered Acanthostega who, at approximately 365-million-years old, is the most primitive tetrapod known.

Ultimately, we (and all the other vertebrates) are descended from Acanthostega or one of her cousins. The point is, this little beauty had eight fully evolved fingers on each hand (Fig.1). So, if evolution hadn't taken a slight detour, we could have been wizards at typing while also ending up using a hexadecimal (base-16) numbering system. As we discovered in my previous column (*PE*, May 2023), having sixteen fingers and being familiar with hexadecimal would have been jolly handy (no pun intended) when we finally got around to inventing computers.

Why once? Why repeatedly?

A reader we will call Andrew (because that's his name) emailed me to say he had a question pertaining to the `setup()` and `loop()` functions we use when creating Arduino sketches (programs). These functions are automatically instantiated for us when we use the Arduino's integrated development environment (IDE) to create a new sketch (Listing 1).

Andrew said that he fully accepts that the `setup()` function will run only one time while the `loop()` function will run over and over again, but that he doesn't understand what makes things work this way and could I possibly explain.



```
void main() {
  setup();
  while(1) loop();
}

void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:

}
```

Listing 2. Ah! That explains it!

When we look at these functions, there's nothing to distinguish them except their names, so why *do* they work differently? Have you ever wondered about this yourself? If so, why didn't you email me rather than leaving everything up to poor old Andrew? I am, of course, more than happy to elucidate, explicate, and expound on this topic (as I've said many times before, much like my dear old mother, the real trick is to get us to *stop* waffling).

Here's the deal. In the real world, every C/C++ program commences with a `main()` function. If we were to explicitly show this function in our Arduino sketches, it would look something like Listing 2 (the real-world Arduino incarnation is a tad more involved, but that's nothing we need concern ourselves with here).

As we see, the first statement in our hypothetical `main()` function calls our

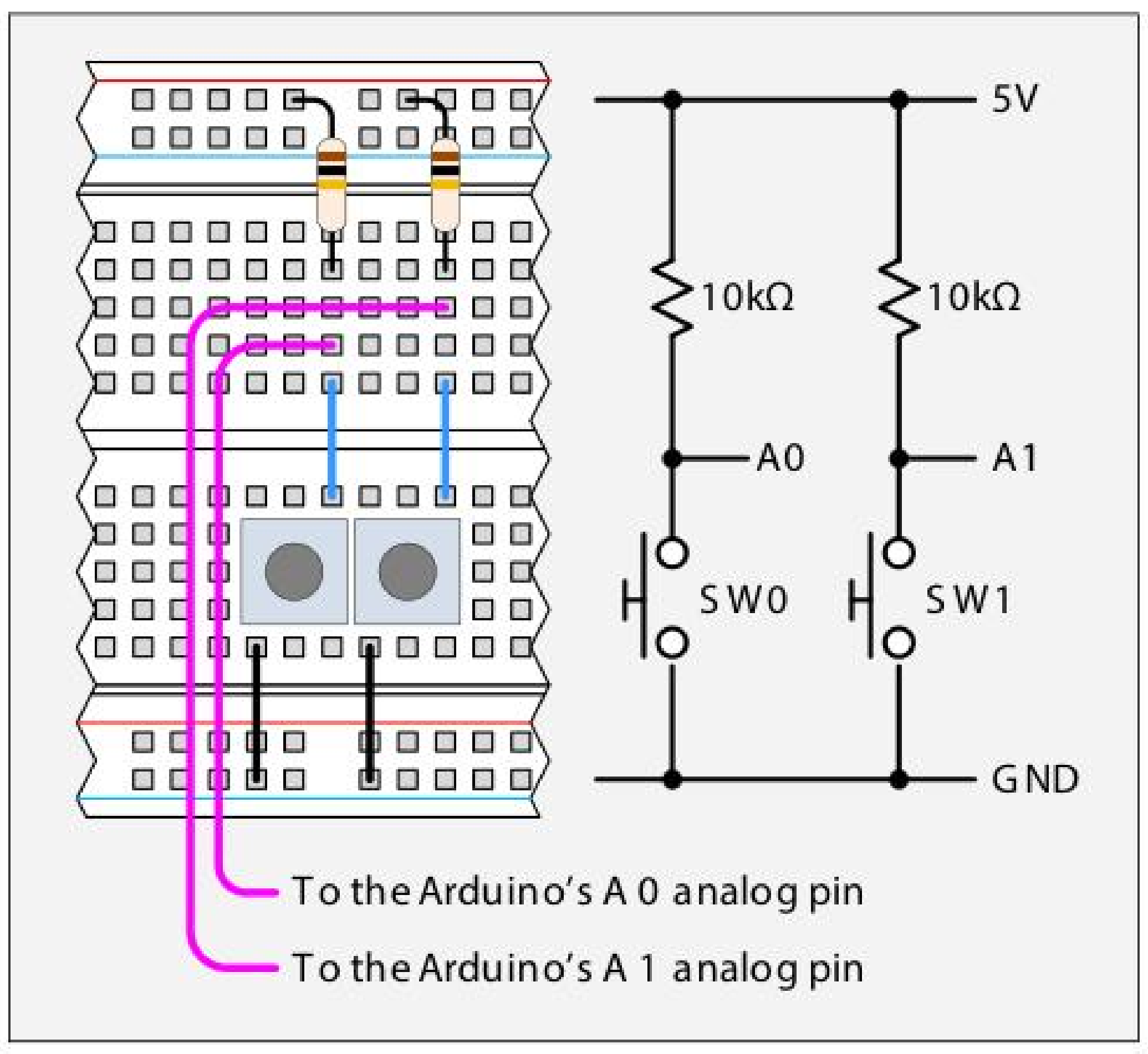

5V
10kΩ
10kΩ
A0
A1
SW0
SW1
GND
To the Arduino's A 0 analog pin
To the Arduino's A 1 analog pin

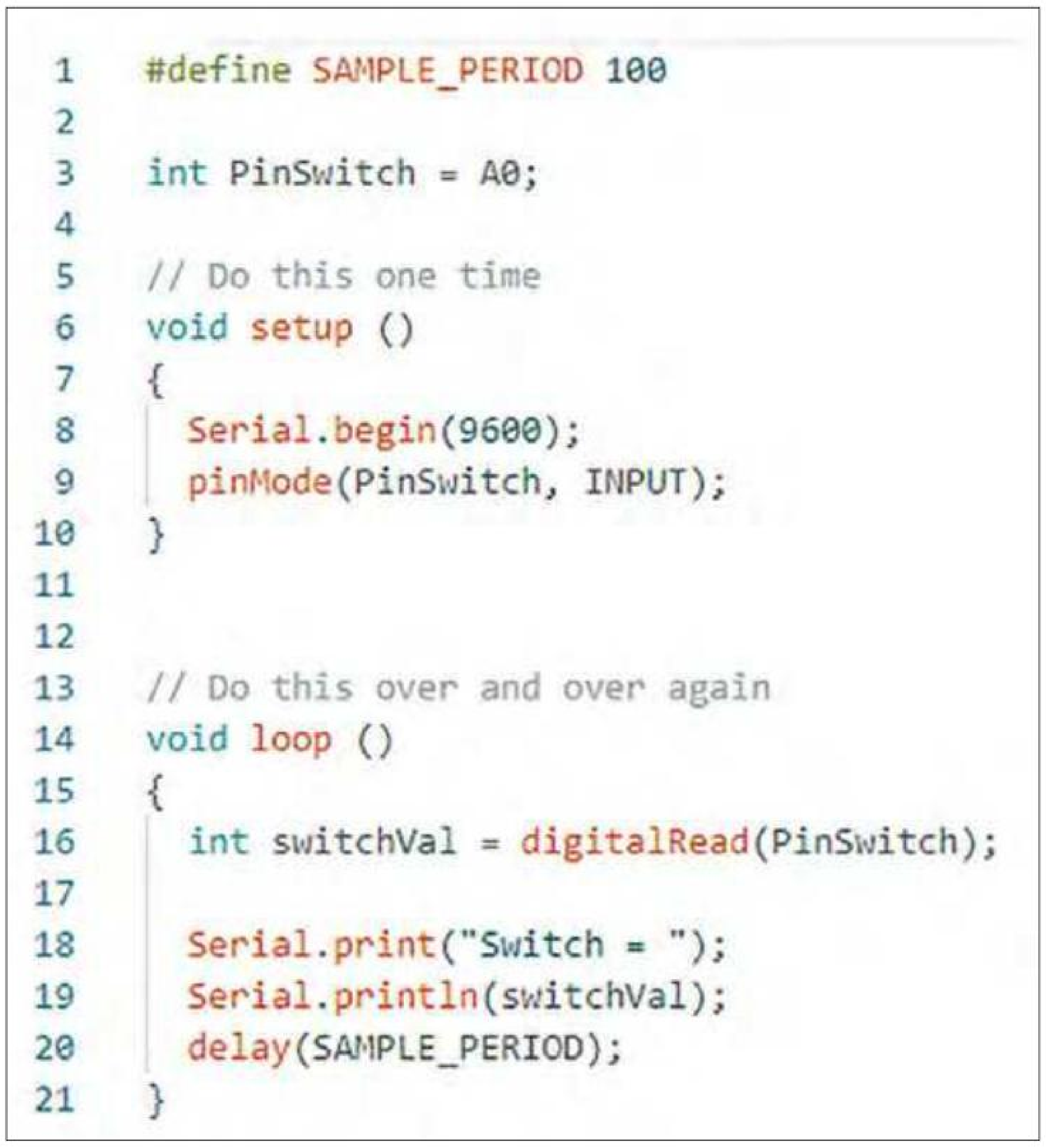
Fig.2. Adding a second pushbutton switch.

`setup()` function a single time. With respect to the second statement, remember that the Arduino sees `1`, `HIGH`, and `true` as being the same thing; hence, `while(1)` is the same as saying `while(true)`. Since this condition, by definition, always returns `true`, the `while(1)` statement will repeatedly call our `loop()` function.

The creators of the Arduino wanted to keep things as simple as possible to get users up and running as quickly as possible. Based on this philosophy, they decided to hide a lot of nitty-gritty details 'under the hood,' as it were. One of these details was the `main()` function, which is automatically slipped in by the Arduino's IDE while you aren't looking whenever you compile your programs.

The loneliest number

I've said before and I will doubtless say it many times again – if there is one song that sets my teeth on edge, that song is *One* (popularly known as *One is the Loneliest Number*), which was written by Harry Nilsson and made famous by the American rock band Three Dog Night in 1968.



```
1   #define SAMPLE_PERIOD 100
2
3   int PinSwitch = A0;
4
5   // Do this one time
6   void setup ()
7   {
8     Serial.begin(9600);
9     pinMode(PinSwitch, INPUT);
10  }
11
12
13  // Do this over and over again
14  void loop ()
15  {
16    int switchVal = digitalRead(PinSwitch);
17
18    Serial.print("Switch = ");
19    Serial.println(switchVal);
20    delay(SAMPLE_PERIOD);
21  }
```

Listing 3. First switch test program.

Having said this, it must be admitted that the solitary pushbutton switch we used in our previous experiments did look a little lonely. This is why, toward the end of my previous column, I asked you to add a second switch (with associated pull-up resistor) to your breadboard to keep the first switch company. I also asked you to connect the output from this switch to pin A1 on your Arduino. The result should look something like Fig.2.

To ensure we are all marching in lockstep, you can download a copy of our current breadboard layout showing both switches, our 7-segment display, and the connections to our Arduino Uno (file **CB-Jun23-01.pdf**). As usual, all the files mentioned in this column are available from the June 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

We will be using both these switches shortly, but first we have a little catching up to do.

Mission impossible

I used to enjoy watching the television series *Mission Impossible* in the late-1980s (I only recently discovered that this was a continuation of an earlier series from the mid-1960s). Each episode started with the team leader receiving a tape describing the mission *du jour*, and each tape commenced with the iconic phrase, 'Your mission, should you choose to accept it…'

As you may recall, the last experiment we performed in the previous column was to create a test program that looped around reading from our first pushbutton switch and writing its current 0 or 1 value to the Arduino's Serial Monitor on our computer screen (Listing 3, file **CB-Jun23-02.txt**).

I then said something along the lines of, 'Your mission, should you choose to accept it, is to use the minimum number of modifications necessary to tweak our existing decimal count program so that, after bidding us 'HELLO,' it loops around reading the state of the switch and displaying corresponding 0 and 1 values on the 7-segment display.'

How well did you do? I bet you were magnificent! How about if I show you how I did it and you can compare your solution to mine? I started by using the Arduino IDE to open our *Auto_Dec_Count_Up* program (you can find a copy in file **CB-Jun23-03.txt**) and saving it as a new program called *Switch_Test_02*.

In the definitions at the top of our new test program I added Line 1 from Listing 3:

```
#define SAMPLE_PERIOD 100
```

I augmented the existing pin definitions in our new test program by adding Line 3 from Listing 3:

```
int PinSwitch = A0;
```

In the `setup()` function in our new test program, I specified that our new pin was to be treated as an input by adding Line 9 from Listing 3:

```
pinMode(PinSwitch, INPUT);
```

The last statement in our `loop()` function is a call to the built-in `delay()` function. In the original counting program, we used our `ON_TIME` constant (1000 milliseconds or 1 second) as the argument to this function. I replaced this with our new `SAMPLE_PERIOD` constant (100 milliseconds or 1/10th of a second).

All that remained was to modify the `GetNewDigit()` function. As you will recall, at the heart of the existing function we use the following statement to implement our decimal count.

```
tmpDigit = (DigitToDisplay + 1)
% NUM_DIGITS;
```

All I had to do was replace this statement with a modified version of Line 16 from Listing 3 as follows:

```
tmpDigit = digitalRead(PinSwitch);
```

And that's all there is to it. This really isn't bad when you come to think about it. All we had to do was add three new statements and tweak two of our existing statements, and 'Bob's your uncle' (or aunt, depending on your family dynamic). You can access a copy of this modified program in file **CB-Jun23-04.txt**

When we run this new version of our program, after displaying the 'HELLO' message, it will start to present 1 on the 7-segment display. When we press and hold the momentary pushbutton, the program will present 0 on the display. Try pressing and releasing the pushbutton a few times. I don't know about you, and I don't know why this should be, but I find that watching the display change when I press the pushbutton gives me a certain sense of satisfaction.

Ready, steady, press!

The second task I asked you to perform at the end of the previous column was to return to our *Auto_Dec_Count_Up* program and save this as *Switch_Dec_Count_Up*. In this case, following the 'HELLO' message, we want to commence by presenting a 0 on the display. Next, we want the program to loop around checking the state of our pushbutton switch. Whenever the switch is pressed, we want to increment (add 1 to) the value on the display. As usual, when we reach 9, pressing the switch one more time will cause the display to wrap around back to 0.

Let's do this together. To keep our code concise, we will use 'SW' (or 'sw' or 'Sw' depending on the circumstance) as abbreviations for 'switch.' Remember, when our switch isn't being pressed, the wire connected to the Arduino will be pulled up to 5V by the pull-up-resistor, so the value seen by the Arduino will be 5V (`1` or `HIGH`). By comparison, when the switch is pressed, the value seen by the Arduino will be 0V (`0` or `LOW`). Based on this, we're going to add the following lines to the definitions at the top of our program.

```
#define SW_PRESSED  LOW
#define SW_RELEASED HIGH
```

As before, we will augment the existing pin definitions in our new count program by adding a modified version of Line 3 from Listing 3:

```
int PinSw = A0;
```

In our original auto-count program, we declared a global integer called `DigitToDisplay` to which we assigned a value of `–1`. Since we now wish to start off by displaying `0`, and based on other modifications we're going to make, we are going to change this assignment to `0`, as follows:

```
int DigitToDisplay = 0;
```

There are two changes we need to make to the `setup()` function in our new count program. As before, we will specify that our new pin is to be treated as an input by adding a modified version of Line 9 from Listing 3:

```
pinMode(PinSw, INPUT);
```

We also need to add a new statement right at the end (just before the '}' curly bracket) as follows:

```
DisplaySegs(DigitSegs[0]);
```

Actually, in the real program (file **CB-Jun23-05.txt**), instead of `0` we use our `DigitToDisplay` variable to which we just assigned `0` (I used `0` here to ensure I didn't run out of space).

The last statement in our current `loop()` function is a call to the built-in `delay()` function. We did this to pause after displaying the new auto-count digit, but we no longer need this delay because we are going to control the count with our pushbutton switch, so we can delete this statement from our program.

All we need to do now is modify our `GetNewDigit()` function such that, instead of auto-counting, it only increments our current value to be displayed when we press our switch. If you are a newbie to all this, your knee-jerk solution might be to modify our code to look something like Listing 4.

At a first glance, this certainly seems simple enough. We start on Line 88 by declaring a local variable (ie, a variable whose scope is limited to this function) called `tmpDigit` ('temporary digit') to which we assign the value stored in the global variable `DigitToDisplay` (ie, the current value of the number we wish to display). Next, on Line 89, we declare a local variable called `swVal` ('switch value') to which we assign the value returned when we use the built-in `digitalRead()` function to access the value on the pin connected to our switch.

On Line 91 we use an `if()` control statement to make a decision based on the value we just read from our switch (we introduced the `if()` in *PE*, April 2023). If the switch is pressed, we increment the value in `tmpDigit` using the statement on Line 93. As we discussed in an earlier column (*PE*, April 2023), our use of the `%` modulo operator means that our count will proceed from 0 to 9 and then back to 0 again.

Finally, we return the value in `tmpDigit`. Due to the somewhat clunky way in which we've created our program, this will end up being copied back into `DigitToDisplay` (we had good reasons for employing this technique when we were learning how to do things, and we may as well stick with what we've got for now).

Does this all look good to you? If so, upload this new version of our program into your Arduino. Wait for it to display 'HELLO', pause for a second, and start displaying 0.

Are you ready? Are you steady? If so, press and release your pushbutton switch a few times and see what happens.

What's going wrong?

As you know, what we want is for the value on the display to increment every time we press our pushbutton switch. As you will have discovered, however, this isn't what's happening. Whenever we press the switch, the display shows a value of 8. Whenever we release the switch, the display presents what appears to be a random value between 0 and 9. So, what's going wrong?

Well, the problem is that we're being silly billies. As is often the case, the best way to visualise what's going on is by means of a diagram (Fig.3a).

The 'Test Times' in this illustration reflect every time we execute our `loop()` function, call our `GetNewDigit()` function, and read and test the state of our switch. Since the Arduino Uno's clock is running at 16MHz (16 million times a second), this means we are racing around checking the state of the switch hundreds of thousands of times each second (in turn, this means there would be many more 'Test Times' than are shown in this simple diagram).

The way our current program is set up, every time we read our switch and determine that it's in its pressed state, we increment and display our count value. Thus, the reason we see the number 8 whenever we press and hold our switch is that the Arduino is repeatedly displaying 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. It's doing this so fast that everything is a blur, and it appears to our eyes that all the segments are illuminated all the time. Similarly, when we release the switch, the reason we see what appears

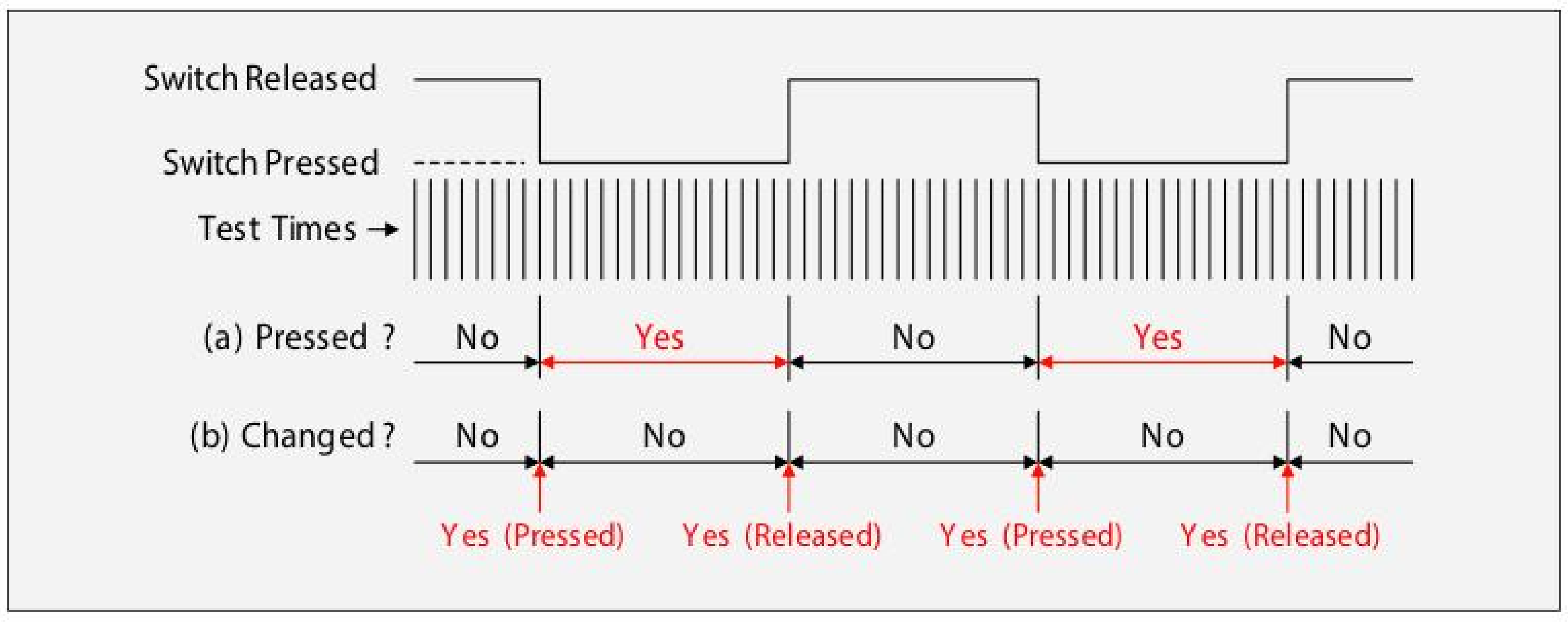
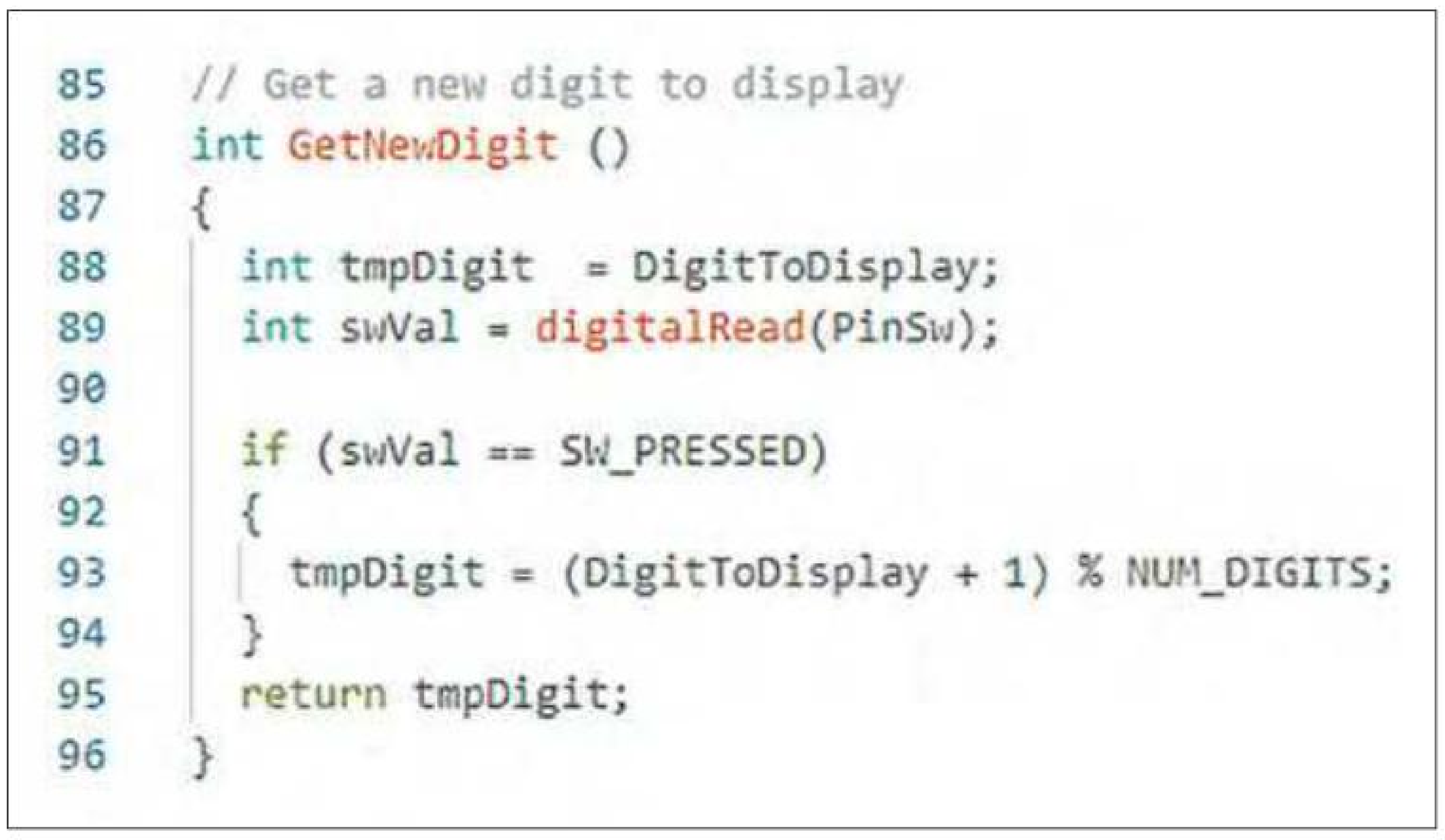


Fig.3. You turn me on.



```
85  // Get a new digit to display
86  int GetNewDigit ()
87  {
88    int tmpDigit  = DigitToDisplay;
89    int swVal = digitalRead(PinSw);
90
91    if (swVal == SW_PRESSED)
92    {
93      tmpDigit = (DigitToDisplay + 1) % NUM_DIGITS;
94    }
95    return tmpDigit;
96  }
```

Listing 4. First pass at using the switch to control the count.

to be a random value between 0 and 9 is that this reflects whatever is the current count value when we release the switch.

Just for giggles and grins, add a `delay(50);` statement at the end of the `loop()` function and upload this new version to your Arduino. This will enable you to see the individual values racing by while you are pressing the switch. Experiment with different delay values like 20 and 200, and then remove this statement before proceeding to our next experiment.

All change!

What we need to do is to modify our code to detect when the state of the switch changes from being released to being pressed, and vice versa (Fig.3b). If you root around various Arduino forums, you will discover that there are myriad ways we can do this. As usual, however, I'm just going to make things up as I go along.

The first thing we're going to require is a global variable to keep track of what we are currently looking for. Let's use an integer called `LookFor` (I'm good with names). Just to keep things simple, let's also assume that, when we first run our program, the switch will be in its released (un-pressed) state. This means we will start off looking for it to be pressed, so we can assign this as part of the declaration as follows:

```
int LookFor = SW_PRESSED;
```

To be honest, this is a bit naughty of us. We should always be careful when making assumptions as to how a user is going to work with a system. In our case, it's not beyond the bounds of possibility that a user would press and hold the switch before powering-up the Arduino. Thus, if we were creating code for use in some mission-critical or safety-critical application, we would read the power-up state of the switch as part of our `setup()` function and assign a value to `LookFor` accordingly.

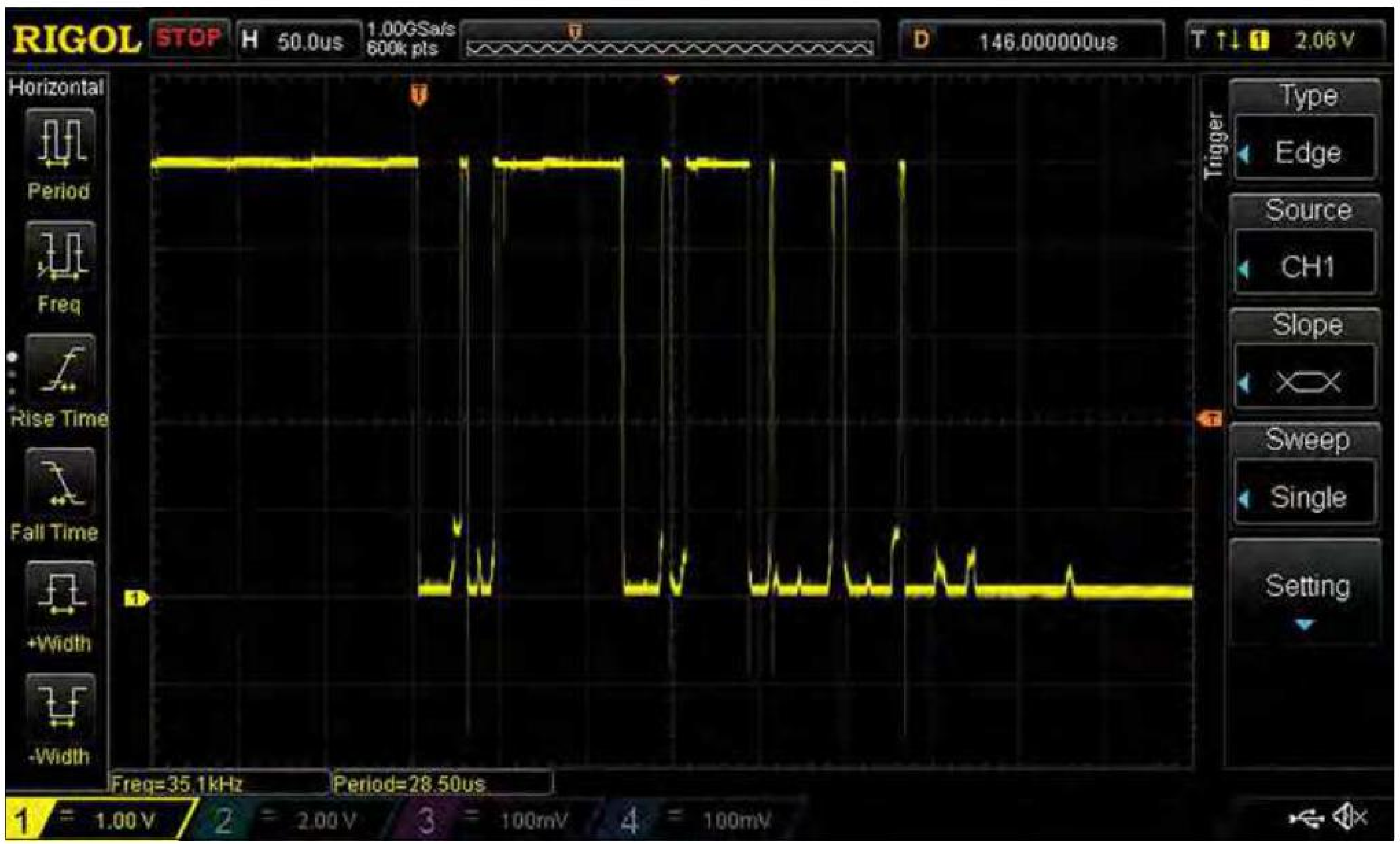
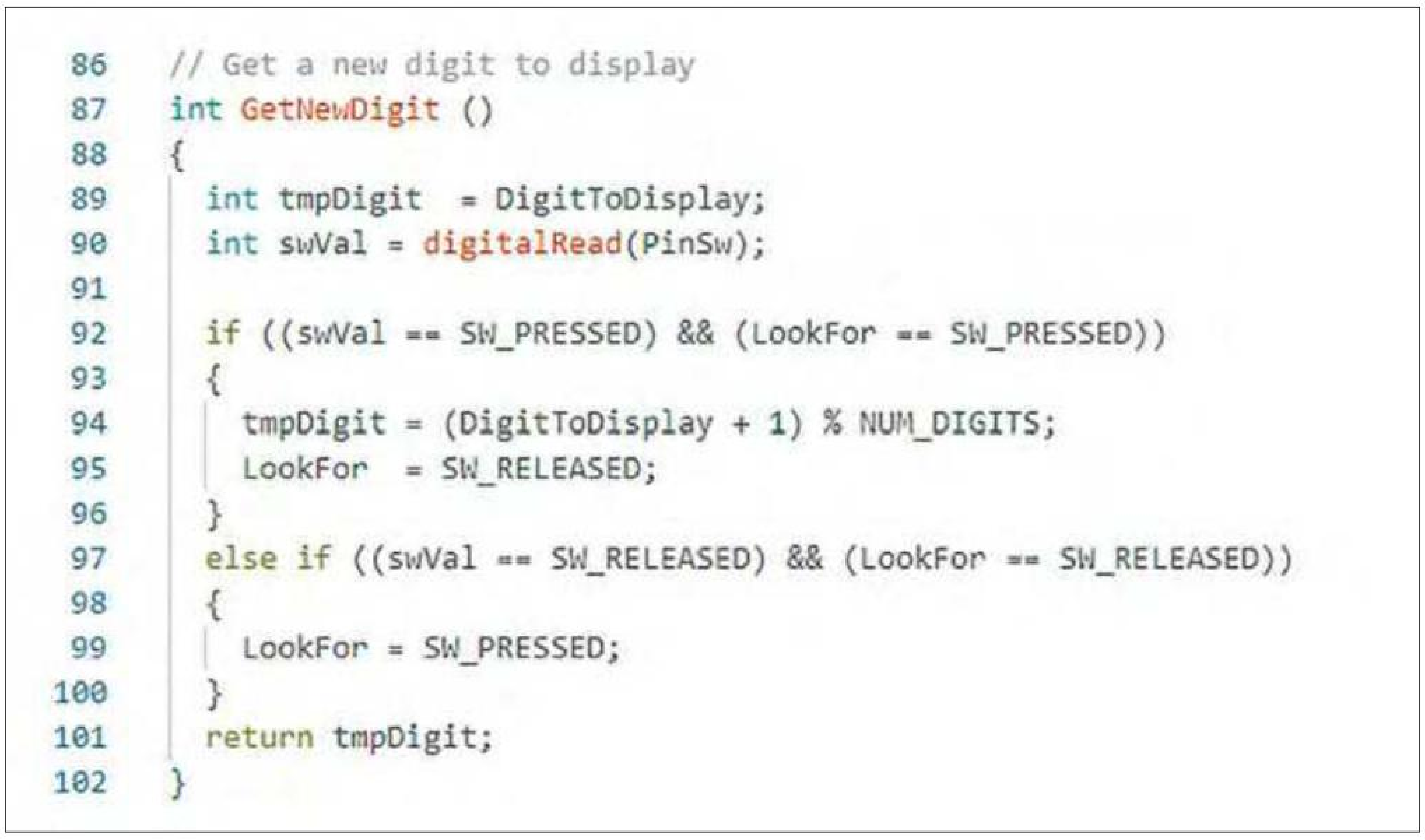


Fig.4. Switches bounce – that's what they do!

The next step is to modify our `GetNewDigit()` function, as shown in Listing 5. First, we check to see if the switch's current value AND the value we are looking for are both equal to `SW_PRESSED`. When we first run the program, this test will fail because the switch is in its `SW_RELEASED` state. When we 'fall through' to the `else if()` portion of the test, we check to see if the switch's current value AND the value we are looking for are both equal to `SW_RELEASED`. In this case, when we first run the program, this test will fail because we are looking for the switch to be in its `SW_PRESSED` state.

We will cycle round and round with nothing changing until the switch is pressed. At that time, the first `if()` test will pass, resulting in our incrementing the value to be displayed and updating the value assigned to `LookFor` to be `SW_RELEASED`.

The next time round the loop, the `if()` test will fail because we are now looking for the switch to be released, and the `else if()` test will fail because the switch is in its pressed state. It's only when the switch is eventually released that the `else if()` test will pass, at which time we will return the value assigned to `LookFor` to be `SW_PRESSED`. (All this is a lot easier to understand than it is to explain.)



```
// Get a new digit to display
int GetNewDigit ()
{
  int tmpDigit  = DigitToDisplay;
  int swVal = digitalRead(PinSw);

  if ((swVal == SW_PRESSED) && (LookFor == SW_PRESSED))
  {
    tmpDigit = (DigitToDisplay + 1) % NUM_DIGITS;
    LookFor  = SW_RELEASED;
  }
  else if ((swVal == SW_RELEASED) && (LookFor == SW_RELEASED))
  {
    LookFor = SW_PRESSED;
  }
  return tmpDigit;
}
```

Listing 5. Second pass at using the switch to control the count.

OK, let's run our latest version of the program (file **CB-Jun23-06.txt**) and see what happens.

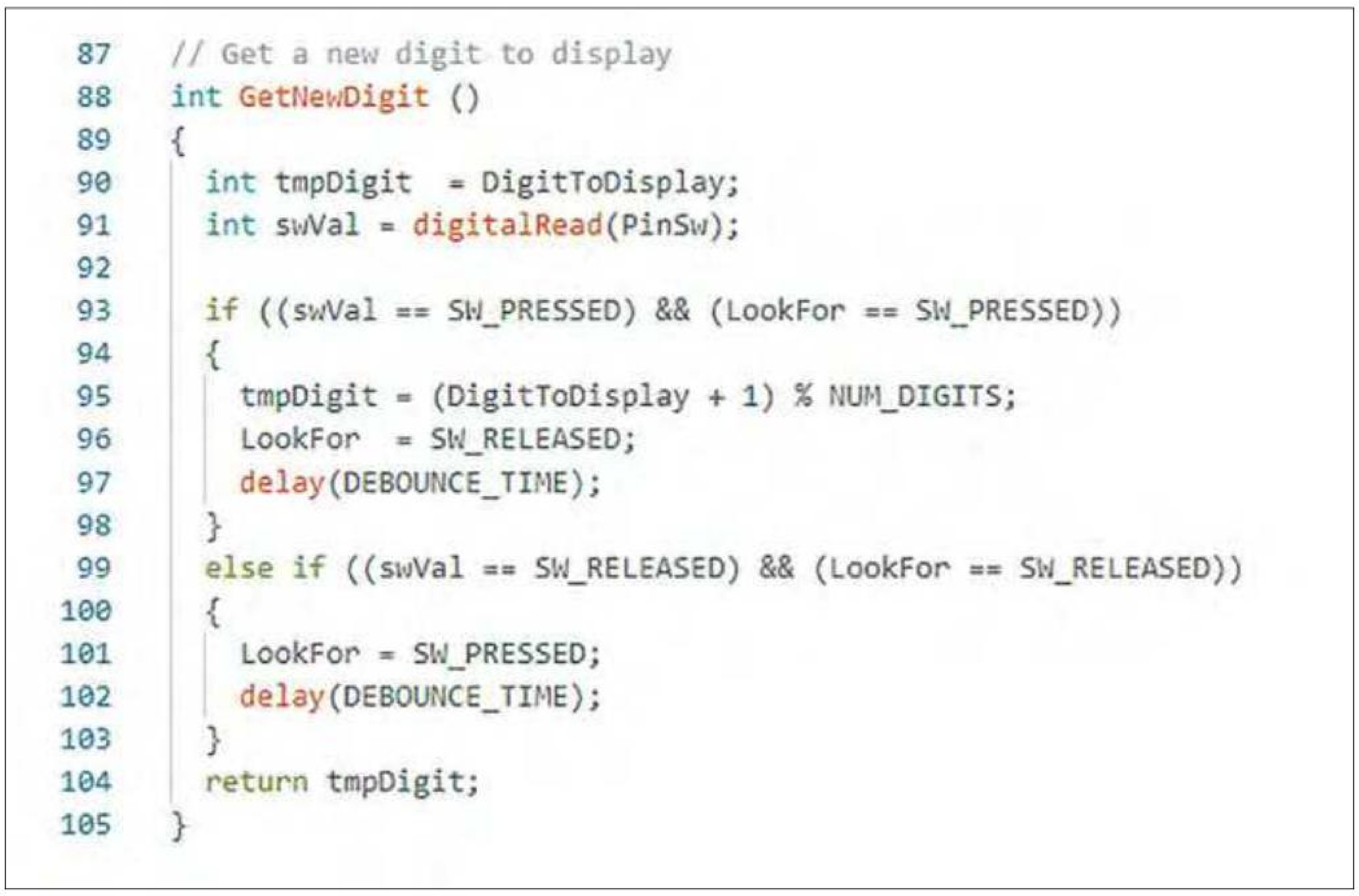
What? More problems?

What happens now largely depends on the switch you are using. It may be that your setup works just the way you expect. That is, when you press the switch, the display value increments, and when you release the switch, things stay 'as-is.' If so, congratulations, you were lucky.

The thing is, switch and relay contacts are usually made of springy metals. When these contacts strike together, their momentum and elasticity cause them to bounce apart one or more times before making steady contact. This affects all sorts of switches, including toggle switches, pushbutton switches, limit switches, reed switches, and so forth. It's possible to see as many as 100+ bounces spanning a duration as great as ~6 milliseconds (ms). Feel free to peruse and ponder my Ultimate *Guide to Switch Bounce* for more details (**https://bit.ly/41e3p14**).

As fate would have it, the first switches I used for this experiment didn't bounce at all, causing me to exclaim 'Oh Dear!' (or words to that effect). Happily, after rooting around in my treasure chest of bits and pieces, I located some switches that bounced like Olympic champions (Fig.4).

In this case, the horizontal scale on my scope is set to 50 microseconds (µS) per division, which means this particular bouncing sequence persists for around 0.3ms. As a result, when I press my switch, the value on my display increases by some random amount depending on the number of bounces.



```
// Get a new digit to display
int GetNewDigit ()
{
  int tmpDigit  = DigitToDisplay;
  int swVal = digitalRead(PinSw);

  if ((swVal == SW_PRESSED) && (LookFor == SW_PRESSED))
  {
    tmpDigit = (DigitToDisplay + 1) % NUM_DIGITS;
    LookFor  = SW_RELEASED;
    delay(DEBOUNCE_TIME);
  }
  else if ((swVal == SW_RELEASED) && (LookFor == SW_RELEASED))
  {
    LookFor = SW_PRESSED;
    delay(DEBOUNCE_TIME);
  }
  return tmpDigit;
}
```

Listing 6. Third pass at using the switch to control the count.

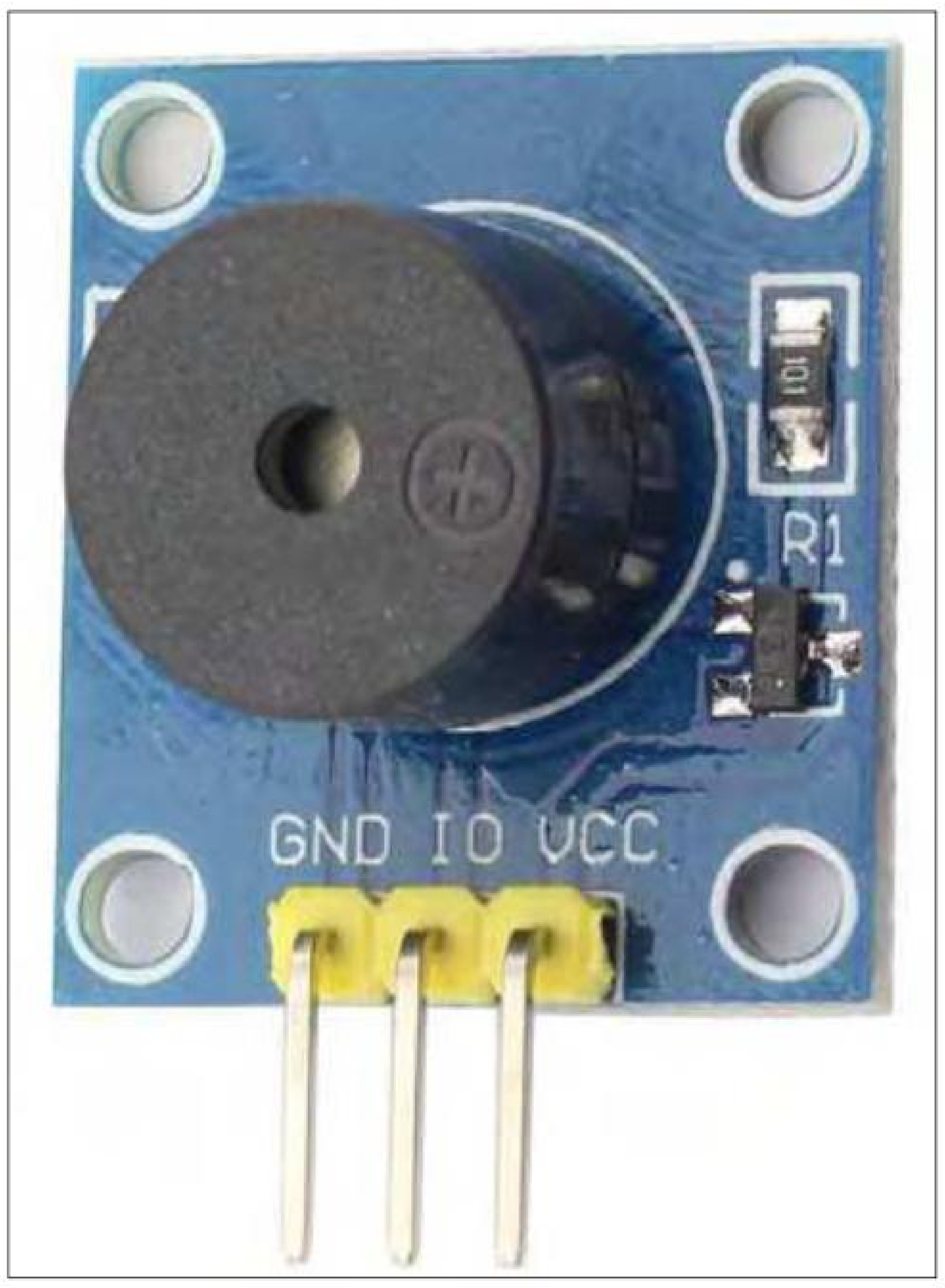


Fig.5. Passive piezoelectric buzzer.

What we need to do is debounce the signal we are receiving from the switch. Purely in the spirit of proof of concept (POC), what we are going to do is assume that any switch bounce will have terminated by 8ms after the switch has been activated (pressed) or de-activated (released). We will add a new definition to our program.

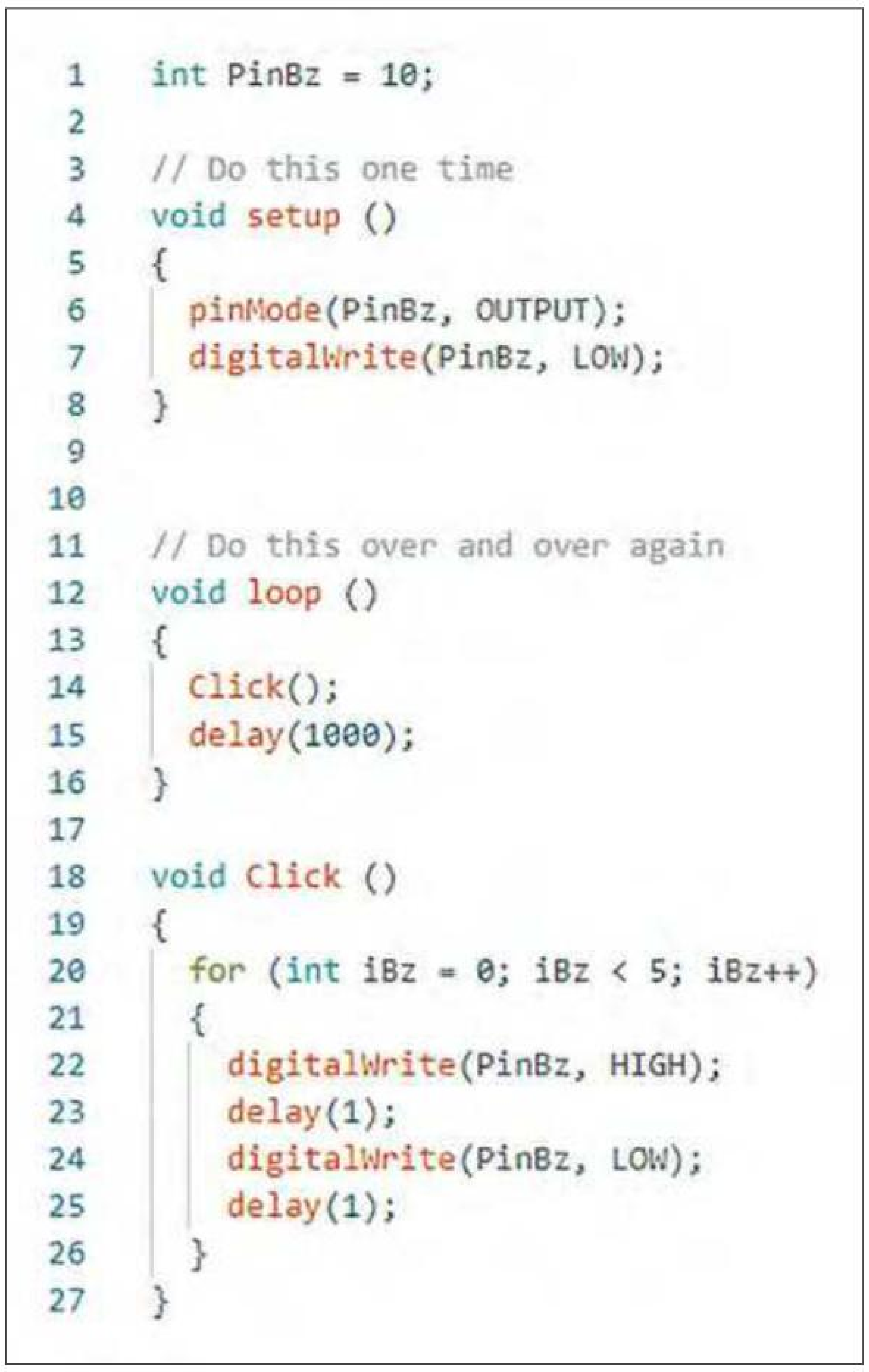
```
#define DEBOUNCE_TIME 8
```

Also, we will modify our `GetNewDigit()` function, as shown in Listing 6. As we see, whenever we detect that the switch has been pressed, we pause for the debounce time before returning control to the main program, and similarly when the switch is released.

Since this delay is only eight thousandths of a second, it's imperceptible to our human senses, but it's more than sufficient for our purposes. When we now run the latest and greatest version of our program (file **CB-Jun23-07.txt**), everything finally works as we wish.

Naughty, naughty!

I should point out that, although it serves our purpose here, the debouncing scheme we just introduced is flaky and shaky, and that's if we're being generous. I would be obliged to chastise myself soundly and hang my head in shame if anyone were to see this in a real-world program.



```
int PinBz = 10;

// Do this one time
void setup ()
{
  pinMode(PinBz, OUTPUT);
  digitalWrite(PinBz, LOW);
}


// Do this over and over again
void loop ()
{
  Click();
  delay(1000);
}

void Click ()
{
  for (int iBz = 0; iBz < 5; iBz++)
  {
    digitalWrite(PinBz, HIGH);
    delay(1);
    digitalWrite(PinBz, LOW);
    delay(1);
  }
}
```

Listing 7. Piezo buzzer click test program.

We will ponder the potential problems with our current debounce solution and consider various improvements in our next column, but first…

Well, buzz me!

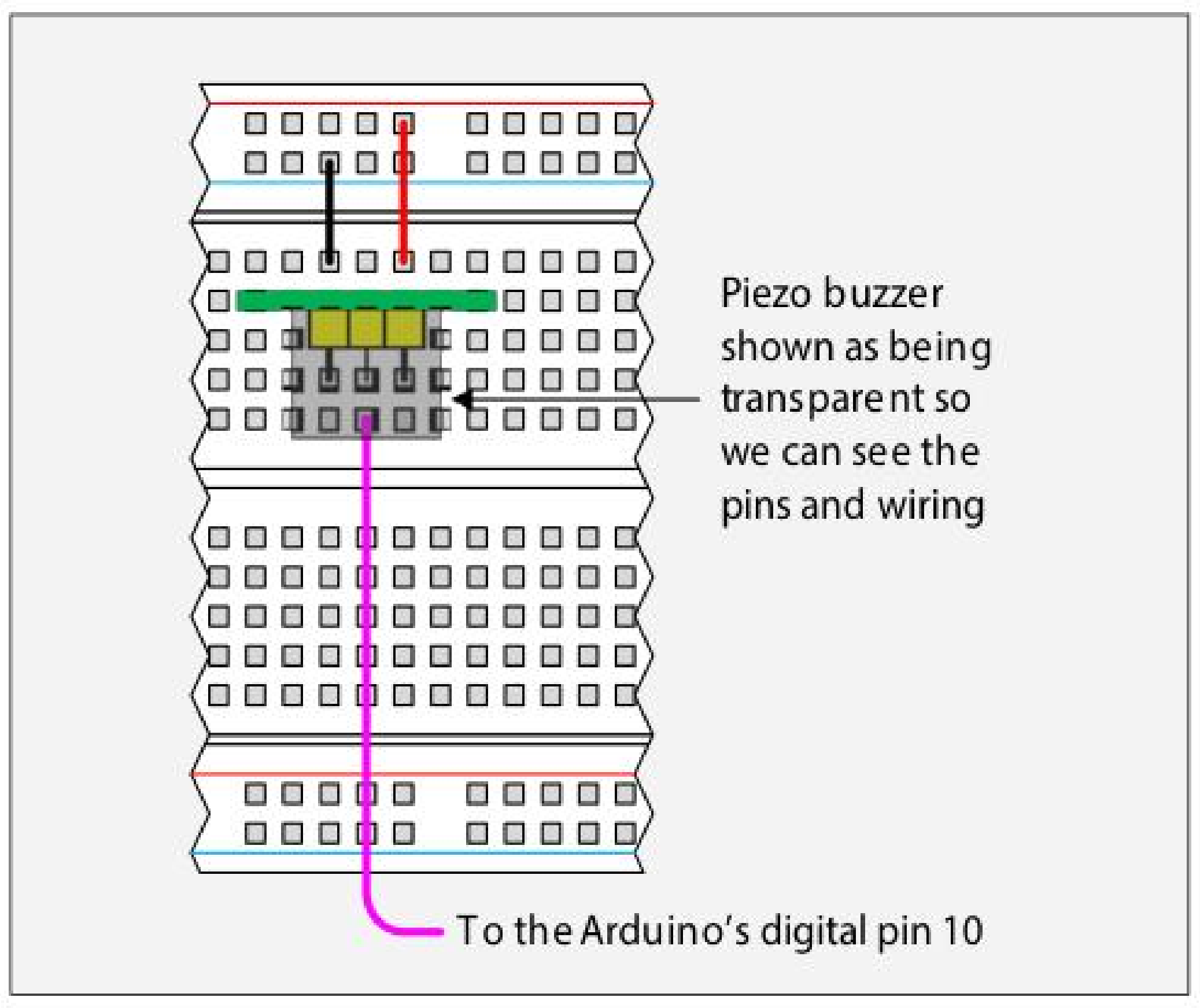
As I promised at the beginning of this column, we're going to use a passive piezoelectric buzzer to super-size the 'click' sounds that occur when we press our momentary pushbutton switches.

Piezoelectricity is the electric charge that accumulates in certain solid materials like crystals and some ceramics in response to applied mechanical stress. One aspect of this is that these materials can be used to form a variety of sensors, including microphones. Conversely, those same materials will deform (change their static dimension) when an external electric field is applied. This inverse piezoelectric effect can be used to create actuators, such as buzzers, that produce sound and ultrasound.

There are two types of piezoelectric buzzers that are commonly used in electronic projects. These are classed as active and passive. In addition to its piezo element, an active piezo buzzer has a few extra components. All this 2-pin device requires is a DC voltage to produce sound but (at least as far as we're concerned here) it can generate only a single frequency. By comparison, a passive piezo buzzer boasts a troika of pins: power (we will be using 5V), ground (0V), and an input signal. Finagling the input makes our lives a little more complicated, but we can control the little rascal to generate a wide range of frequencies and sounds, including musical notes.

For the purposes of our experiments, I purchased a simple passive piezoelectric buzzer for $6.59 here in the US (**https://amzn.to/3nTZ0Ce**). The closest equivalent I could find in the UK costs £12.89 (**https://amzn.to/3KmxjcX**). The great thing about this little scamp is that it is presented on a small breakout board (BOB) with three pins that allow it to be plugged directly into our breadboard (Fig.5).

Speaking of breadboards, let's plug this buzzer into ours and connect its signal pin (shown as 'IO' in Fig.5) to our



Piezo buzzer shown as being transparent so we can see the pins and wiring

To the Arduino's digital pin 10

Fig.6. Piezoelectric buzzer on breadboard.

Arduino's digital pin 10, as illustrated in Fig.6). For your delectation and delight, you can download a copy of our latest and greatest breadboard layout showing both switches, our 7-segment display, our piezo buzzer, and all the connections to our Arduino Uno (file **CB-Jun23-08.pdf**).

Step by step

If I've taught you anything, I hope it includes taking things step-by-step and performing some simple software tests to ensure any new hardware works before we start bolting it into a larger, more complex program. For example, may I make so bold as to suggest you create a program similar to the one shown in Listing 7 (file **CB-Jun23-09.txt**)?

On Line 1 we declare an integer called `PinBz` and assign it a value of 10. This is the pin we're going to use to control our piezoelectric buzzer. Our `setup()` function contains only two lines. First, we set the pin connected to our buzzer to be of type `OUTPUT`, after which we drive it `LOW`. Similarly, our `loop()` function contains only two lines. First, we call a function we're calling `Click()`, and then we wait for a second before doing it all again.

The `Click()` function is just a little something I threw together. All we do is loop around some number of times (5 in this example) driving our buzzer pin HIGH and LOW with 1ms delays between transitions.

Running this first-pass program results in a click sound, albeit one that's a tad tinny. Once we've performed our final experiment for this column, I'm going to experiment with different values for the number of cycles and the delays to see what happens, and I think it would be a good idea for you to do the same.

Clickety Click!

This is where we bring everything together. What we are going to do is to take most of the contents of our click test program and add them to our current switch-controlled count program.

Specifically, we are going to copy Line 1 from Listing 7 over 'as-is.' We are going to add Lines 6 and 7 from Listing 7 into our count program's `setup()` function. Also, we are going to copy the entire `Click()` function from Listing 7 (Lines 18 through 27) and paste it into our count program.

All that remains is to take the call to the `Click()` function (Line 14 from Listing 7) and add it into the main program (between Lines 96 and 97 in Listing 6). The result is a program that increments the display when we press our switch, with each press being accompanied by an extremely satisfying click.

I don't know about you, but I certainly feel a little 'Tra-la' is in order.

Over to you

Now, I want you to be brave because I'm going to leave you in charge. Your first mission is to modify our latest and greatest switch-controlled 'count with click' program so that it reacts to both of our pushbutton switches. Our original switch will continue to increment the count, while the second switch will decrement the count.

Once you have this working, your next task is to 'tweak' things so that each switch has its own unique click sound. I have every faith that you can do this. Make me proud.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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Circuit Surgery

Regular clinic by Ian Bell

Comparator circuits

Last month, based on a post by user Maddan417 on the EEWeb forum, we discussed problems with a voltage comparator circuit using the LM741 op amp. The 741 is a very old design and consequently has limited performance compared with modern devices. We looked briefly at op amp history and how to simulate the 741 in LTspice since it is not 'built in'. We discussed some of the general disadvantages of using op amps as comparators and showed an example simulation highlighting problems with the 741's output voltage and switching speed. However, last month we did not discuss the design of comparator circuits, so this month we will look at comparators and comparator circuit design in more detail.

Comparators and op amps

A comparator is a circuit that compares one analogue signal with another and outputs a binary signal based on the result of the comparison (is one input at a higher or lower voltage than the other?). In effect, it is a one-bit analogue-to-digital converter (ADC).

As discussed last month, op amps can be used as comparators – essentially (at least for basic comparators) they are both very-high-gain differential-input amplifiers with responses down to DC. Therefore, for all but a very small range of input voltage differences, the output will be at the lowest or highest voltage available from the device. These two output voltages can represent Boolean 0 and 1.

Op amps are optimised for use with negative feedback – often in linear circuits such as amplifiers and filters. For op amps, pushing the outputs to the extreme levels referred to as 'saturation' is usually avoided where possible because it tends to degrade performance in linear applications. Also, they tend to be slow in switching operation – as was demonstrated in the simulation last month.

Comparators on the other hand are used open loop (no feedback), or with positive feedback, and are optimised to switch their outputs between the extremes, and to do so quickly. Comparators may have outputs configured very differently from op amps to facilitate interfacing to logic circuits. They may also have positive feedback built-in, although this is often added externally – see the discussion on hysteresis later.

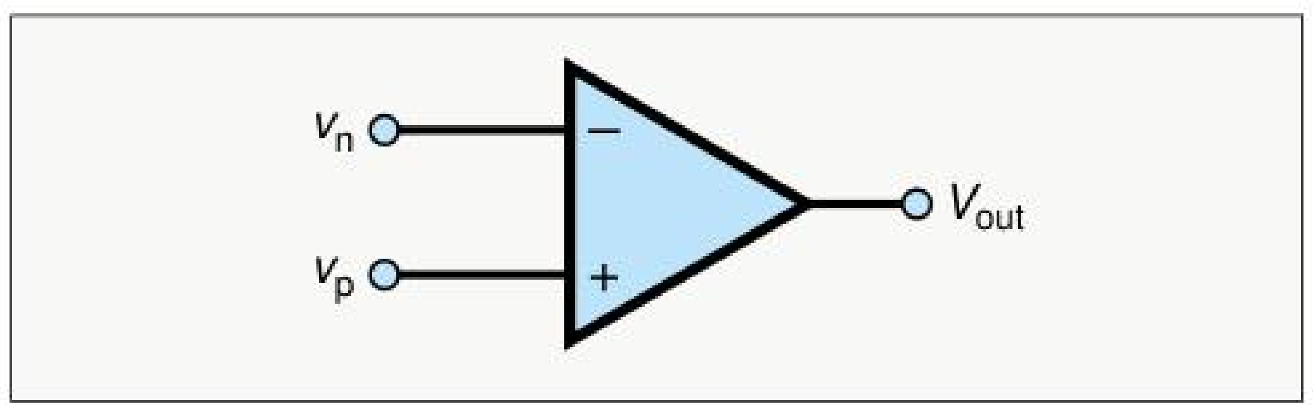


Fig.1. Comparator symbol and signals.

Comparator operation

The circuit symbol for a comparator is shown in Fig.1. A comparator's output voltage may be written mathematically as follows:

$$V_{out} = \begin{cases} V_{OH} & \text{if } v_p > v_n \quad \Rightarrow \text{logic 1} \\ V_{OL} & \text{if } v_p < v_n \quad \Rightarrow \text{logic 0} \end{cases}$$

Where v_p and v_n are the input voltages, as shown on Fig.1, and V_{OH} is the logic 1 (or high) output voltage, and V_{OL} is the logic 0 (or low) output voltage.

Basic comparator circuit configurations

In many applications, comparators are used to compare an input signal with a reference voltage generated within the circuit. In such cases we can configure either inverting or non-inverting operation depending on which of the comparator's inputs is connected to the reference and the input (see Fig.2). A non-inverting comparator has a high output (logic 1) when the input is greater than the reference. For an inverting comparator, a high output is produced when the input is below the reference.

Comparator characteristics

The comparator equation above implies infinite gain and zero offset, V_{OS}. This means that an infinitely small voltage change around the reference voltage (V_{ref}) will cause the output to switch (infinite gain), and that this switching will occur exactly at the applied reference voltage (zero offset).

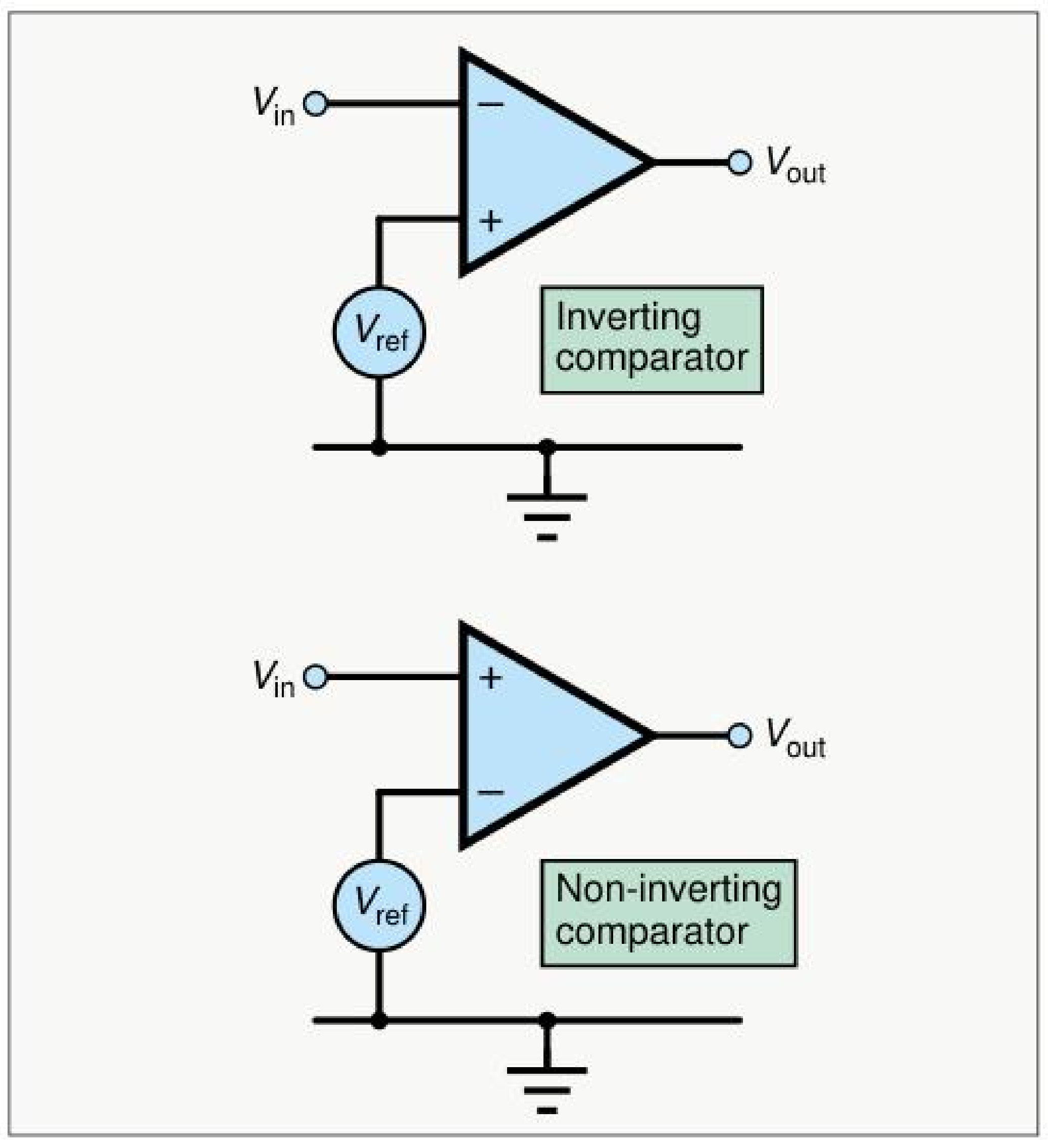


Fig.2. Inverting and non-inverting comparator configurations.

Fig.3 shows the effect of finite gain and non-zero offset on a comparator's transfer characteristic (relationship between input voltage difference and output voltage). The effect of the offset and finite gain is to reduce the resolution of the comparator, so that the difference between the inputs must be larger than a certain minimum to give reliable detection. Fig.3 represents the situation for static inputs, where the resolution is approximately $V_{OS} + V_{IH} = V_{OS} + V_{OH}/\text{gain}$, but typically the resolution will get worse for changing input signals.

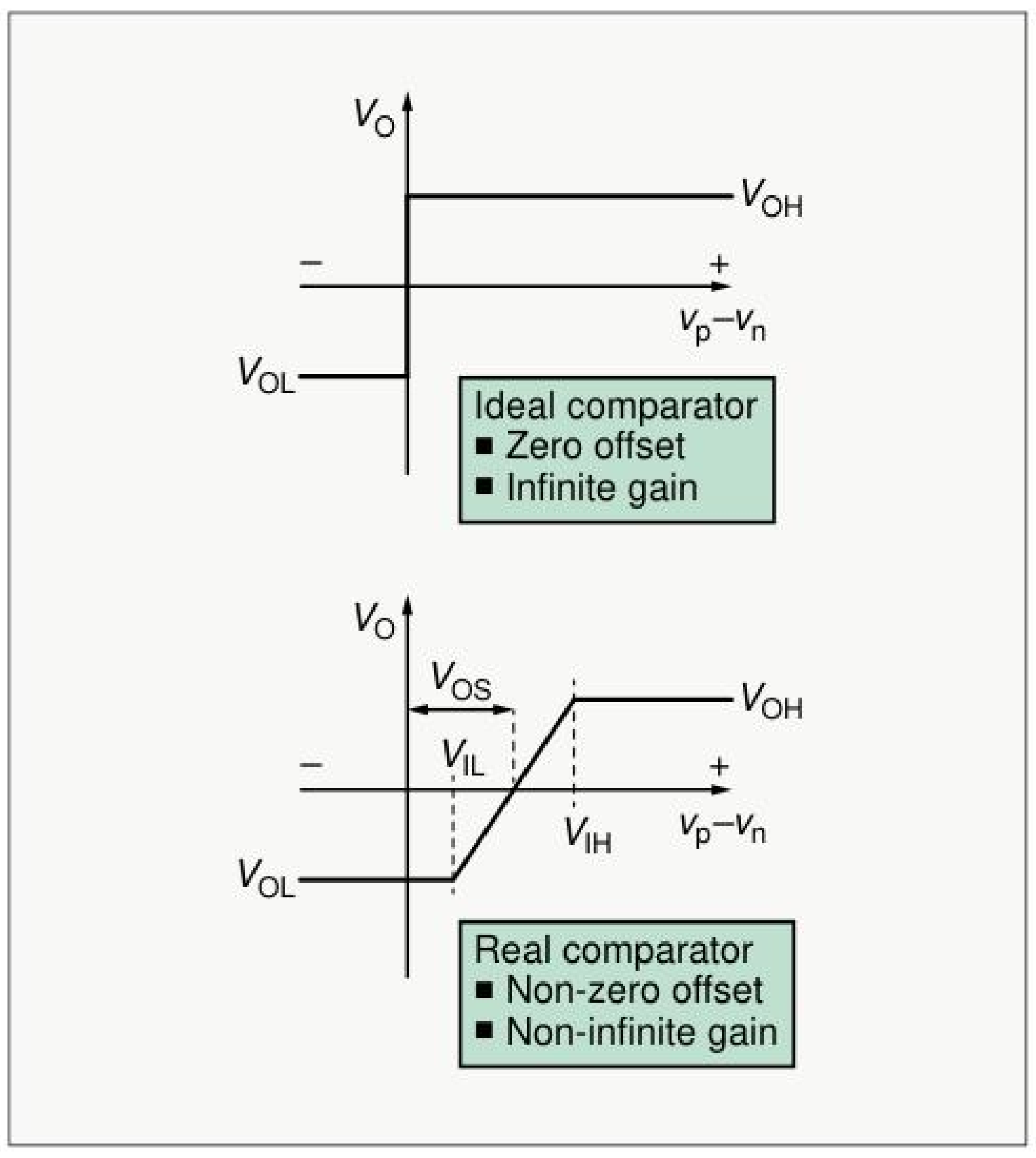


Fig.3. Response of ideal and non-ideal comparators.

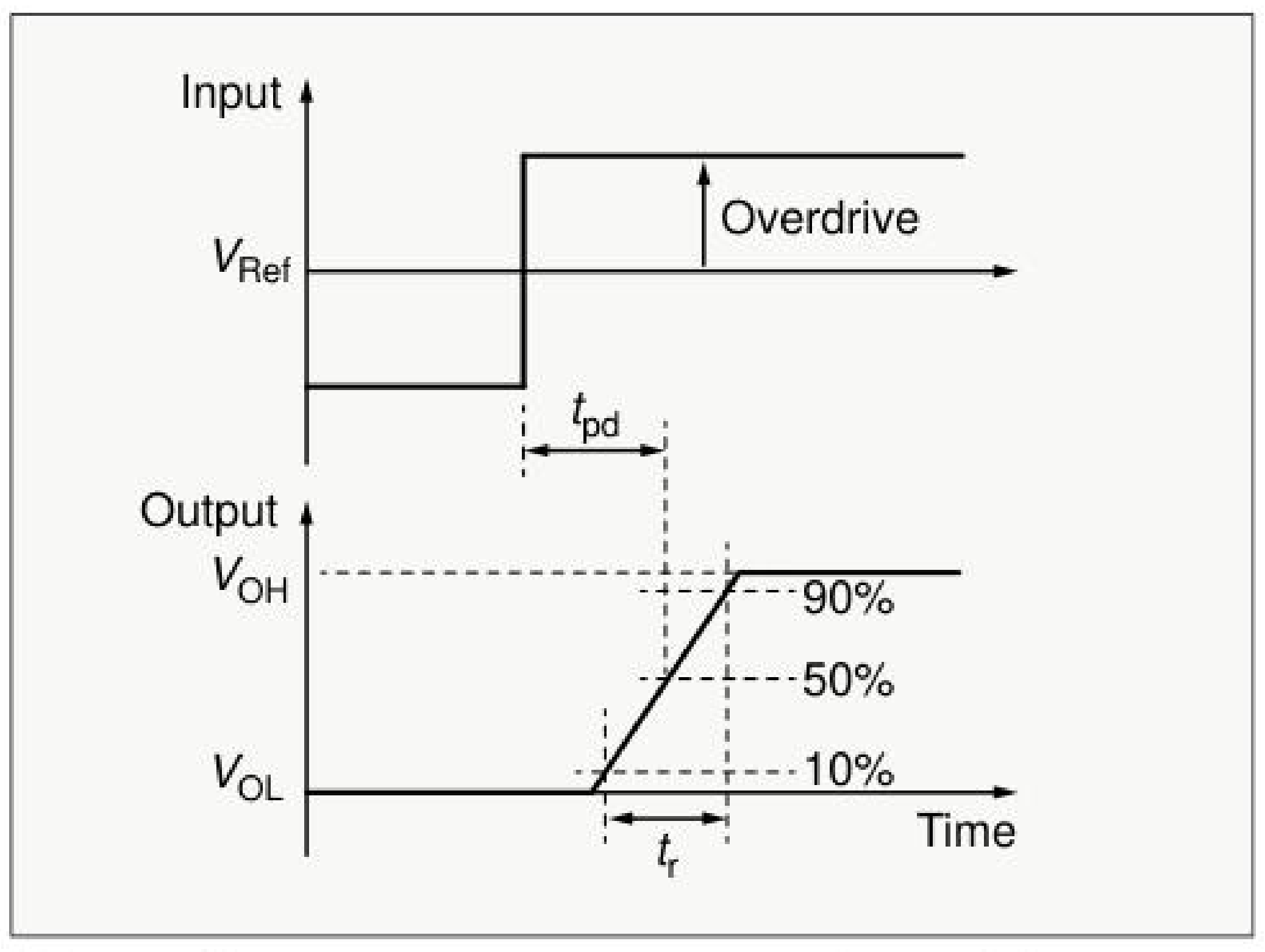


Fig.4. Comparator propagation delay.

The switching characteristics are important for comparators and are illustrated in Fig.4, which shows comparator input and output waveforms for a non-inverting configuration with a fixed reference voltage. Comparator switching characterises are similar to logic circuit device characteristics because the output is essentially digital.

When the comparator input voltage crosses the reference voltage the comparator output will switch. This will not happen instantaneously – the time taken for the comparator output to reach 50% of the resulting voltage change is the propagation delay. The time taken for the comparator output voltage to rise from 10% to 90% of its range is the rise time. Fall time is similarly defined for the output switching in the opposite direction.

The amount of voltage applied to the comparator's input beyond the switching threshold (reference voltage) is known as the overdrive. Propagation delay and rise time are usually sensitive to overdrive, with increasing overdrive resulting in faster switching times. Comparator speed is also usually dependent on supply voltage.

Comparator outputs

The behaviour and circuit design requirements related to the output pin of comparators varies from device to device. This is different from standard op amps, where, although the internal circuitry may be different, the behaviour – aiming for an ideal voltage source – is the same. Of course, the performance (deviations from an ideal source) matter in many applications, but fundamentally all op amp outputs operate in the same way. This is not the case for comparators. There are two main types of output: open collector (or drain) and push-pull.

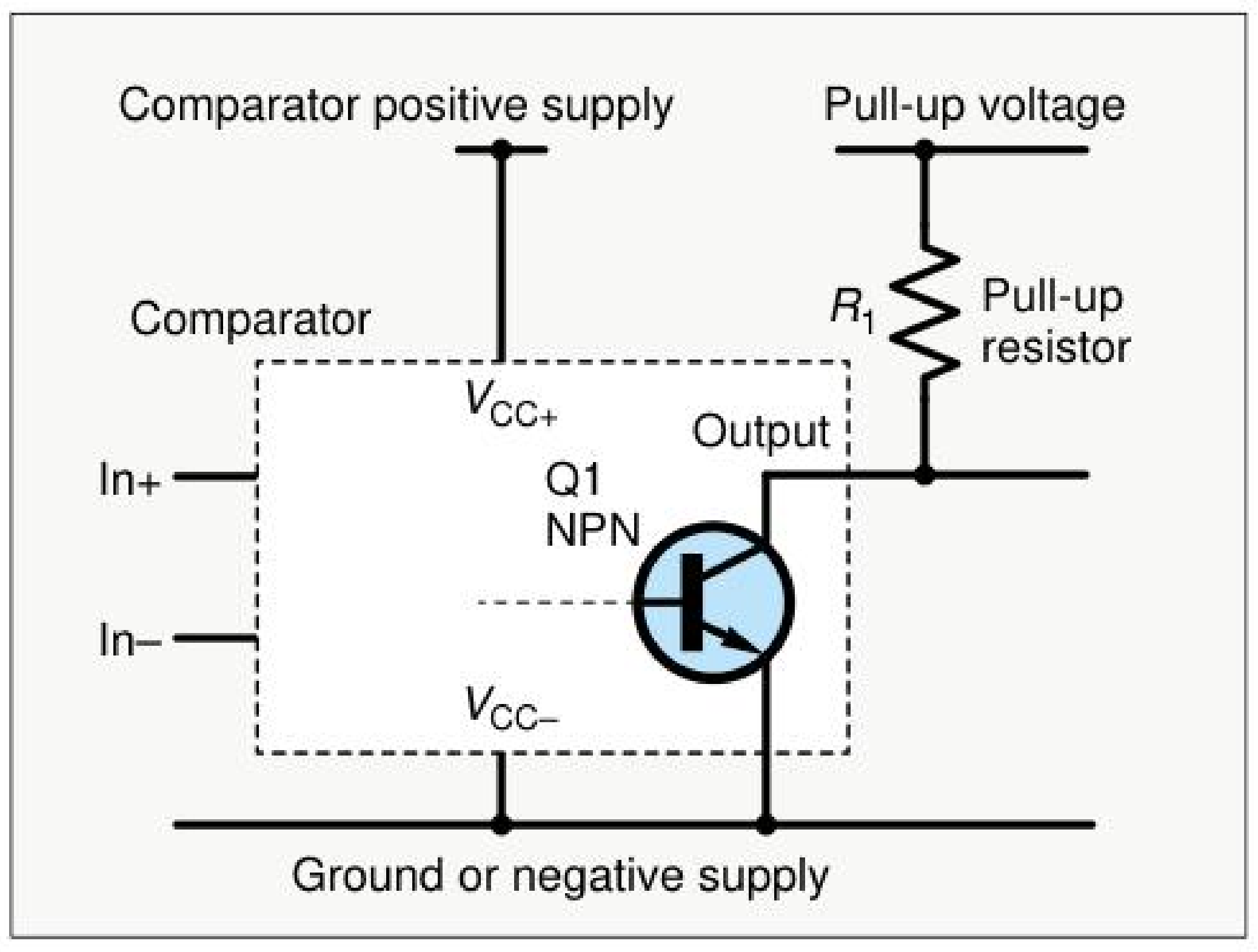


Fig.5. Comparator common-collector output.

There are other differences between comparator devices; for example, some comparators have two complementary outputs (one is the logical NOT of the other – eg, the LT1016) and some have additional functionality which affects the output, such as strobes (eg, LT1011/LM111) and latches (eg, AD790 and LT1016). Device datasheets should always be consulted to check the type of output, supply requirements and use of any special functionality.

Fig.5 and Fig.6 show simplified internal circuitry for open-collector and MOSFET push-pull comparator output stages. The open-collector output (Fig.5) requires a pull-up resistor (R_1) to the high-level voltage (V_{OH} logic 1 voltage). To output the low-level voltage (V_{OL}, logic 0 voltage) the comparator turns on the output transistor (Q1), which pulls the voltage down to close to ground, or to the negative rail on a split supply. To output the high-level voltage the transistor is off, and the resistor pulls the output voltage up to the required level. This approach allows the high-level voltage to be different from the comparator supply voltage, which facilitates voltage translation in circuits where the digital and analogue parts have different supply voltages. A MOSFET can be used in a similar way (open drain).

The push-pull output (Fig.6) uses two complementary transistors (NMOS and PMOS). This is a similar configuration to a logic gate output or half-bridge power switch. One of the transistors is on and one is off, switching the output voltage to either the high or low levels, which are typically equal to the comparator's supply voltages. Some comparators with push-pull outputs have separate supplies (both positive and negative/ground) for the analogue comparison stage and the digital output part. This facilitates interfacing to logic on a different supply voltage from the analogue circuitry. (Note: push-pull outputs can also be built with bipolar transistors.)

An advantage of the open-collector output configuration is that multiple comparators outputs can be connected together with a single pull-up resistor, as shown in Fig.7. This logically combines the outputs – as wired-OR or wired-AND, depending on how you look at it. This use of comparators is often referred to as wired-OR, because if any of the comparators' output transistors are on (ie, the transistor output of U1 OR U2 OR U3 in Fig.7) then the output is pulled low. This is a negative-logic OR. However, if you think of the output voltages as V_{OL} logic 0 and V_{OH} logic 1 (positive logic), then the wired connection acts as an AND, that is all of the comparator outputs have to be outputting logic 1 for the overall output value to be logic 1.

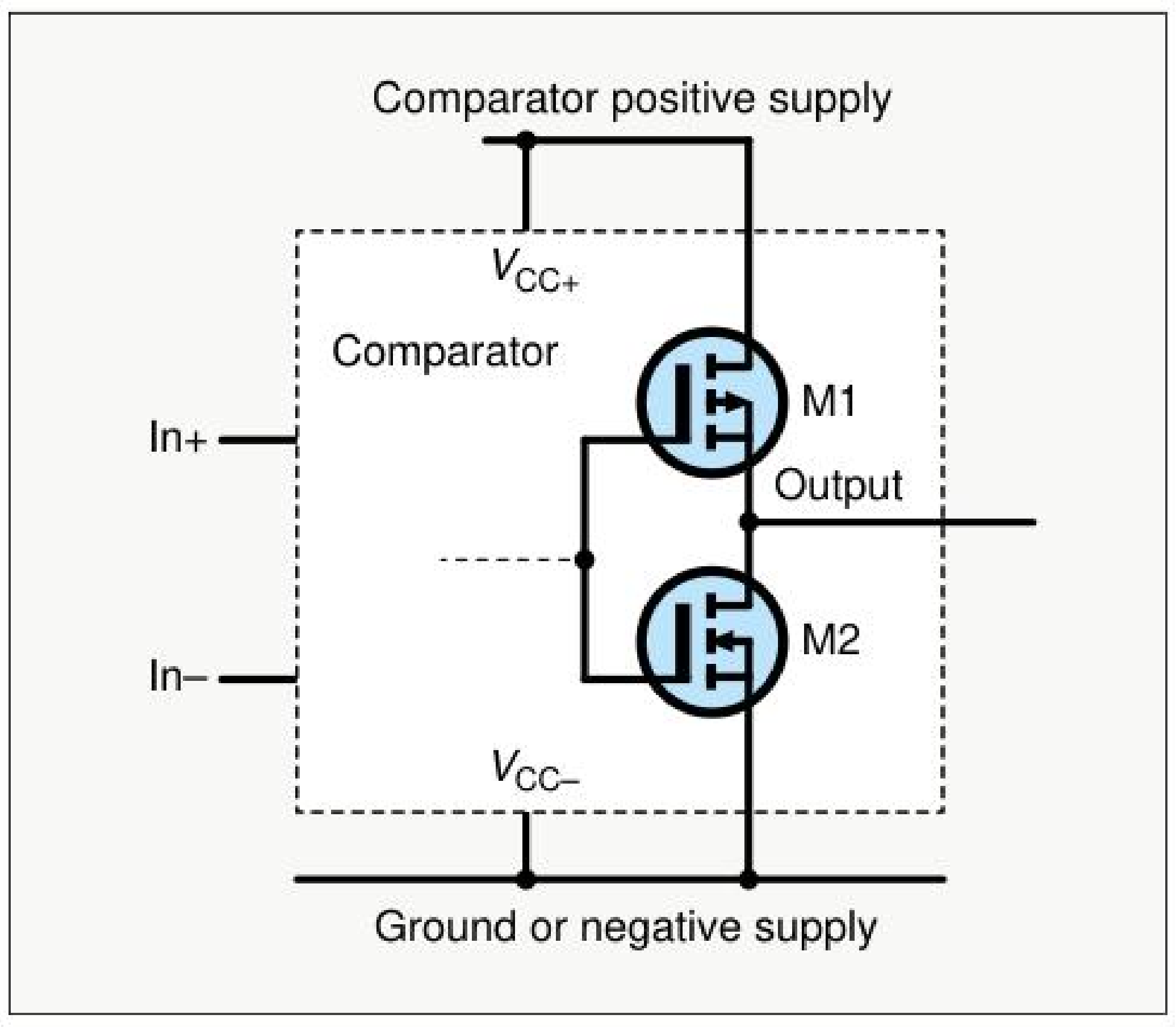


Fig.6. Comparator MOSFET push-pull output.

Window comparator

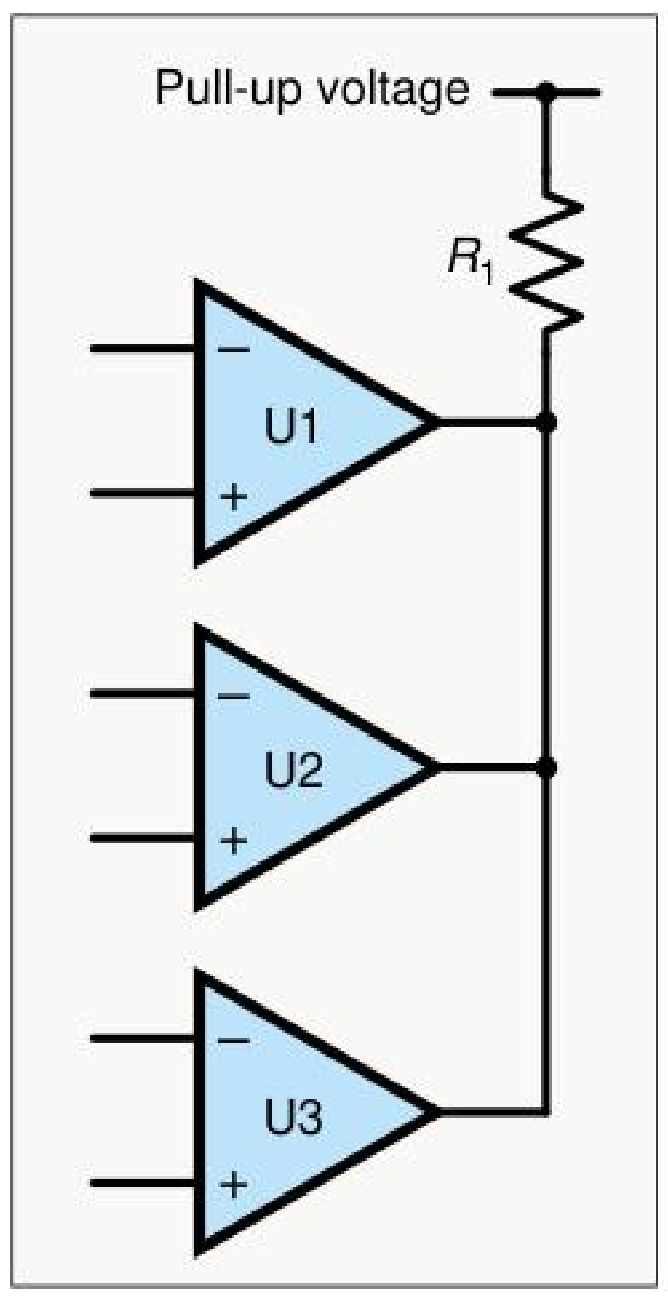
A similar common requirement is to have a single output indicating when an input voltage is within a particular range (ie, above a lower limit V_{refL} but below an upper limit V_{refU}). This is known as a window comparator. It requires two comparators (one inverting and one non-inverting), with the outputs combined with an AND function (above-lower AND below-upper). The AND function can be implemented by a logic gate, but it is common to use comparators with open-collector outputs – see Fig.8.

Hysteresis

A comparator used with a single threshold (reference) value may switch states many times as a noisy, slowly changing input crosses the threshold. This is often undesirable, for example if the number of threshold-crossings is to be counted or you want to avoid 'chattering' when the input is close to the threshold. The problem may be overcome by using two thresholds, high and low: V_{TH} and V_{TL}. The difference between V_{TH} and V_{TL} is called the hysteresis (V_H).

The input-output responses of comparators with hysteresis are shown in Fig.9. When the input *increases* past V_{TH} the comparator switches, but it does not switch back if the input decreases past V_{TH}. The input must decrease past V_{TL} before the comparator switches again.

Fig.7. Common-collector outputs in wired logic combination.



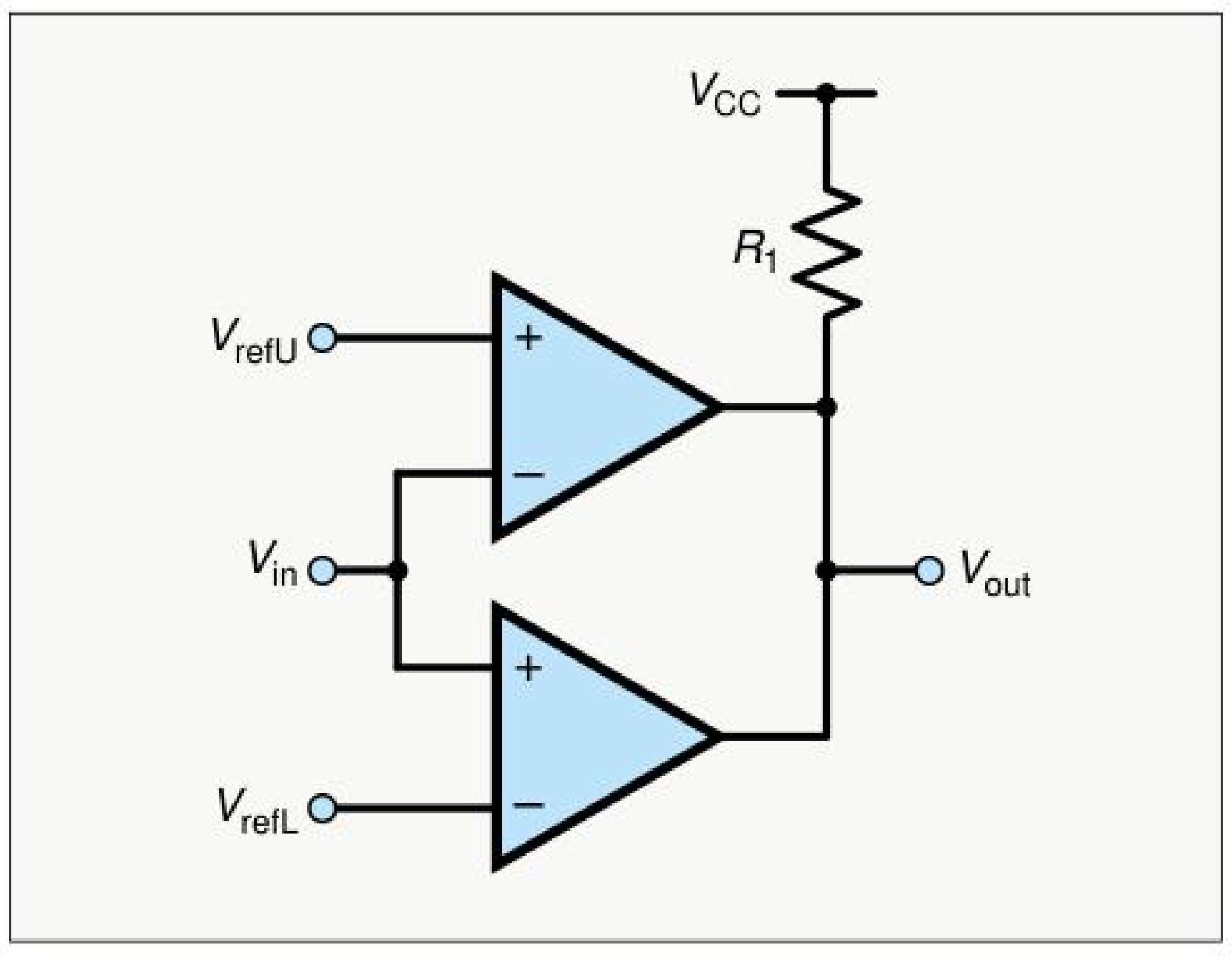

V_{CC}
R_1
V_{refU}
+
–
V_{in}
V_{out}
+
V_{refL}
–

Fig.8. Window comparator using comparators with open-collector outputs.

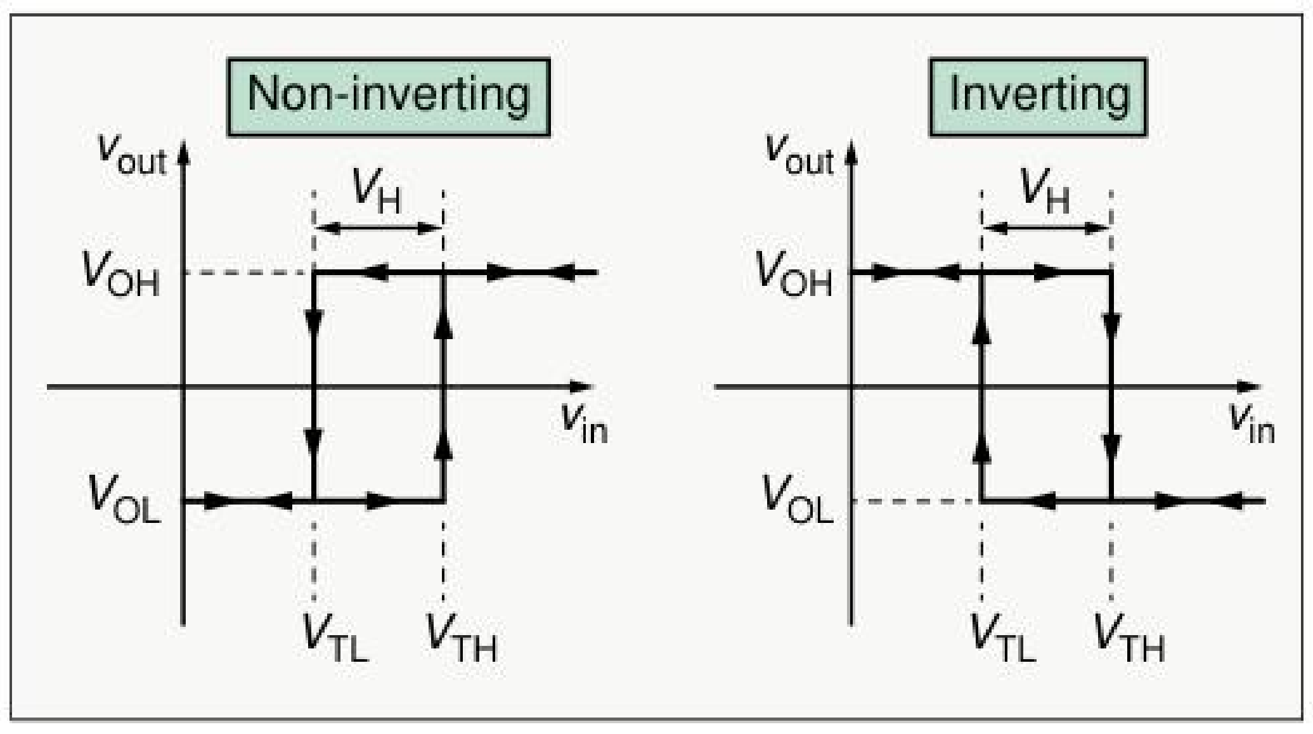


Fig.9. Switching characteristics of comparators with hysteresis.

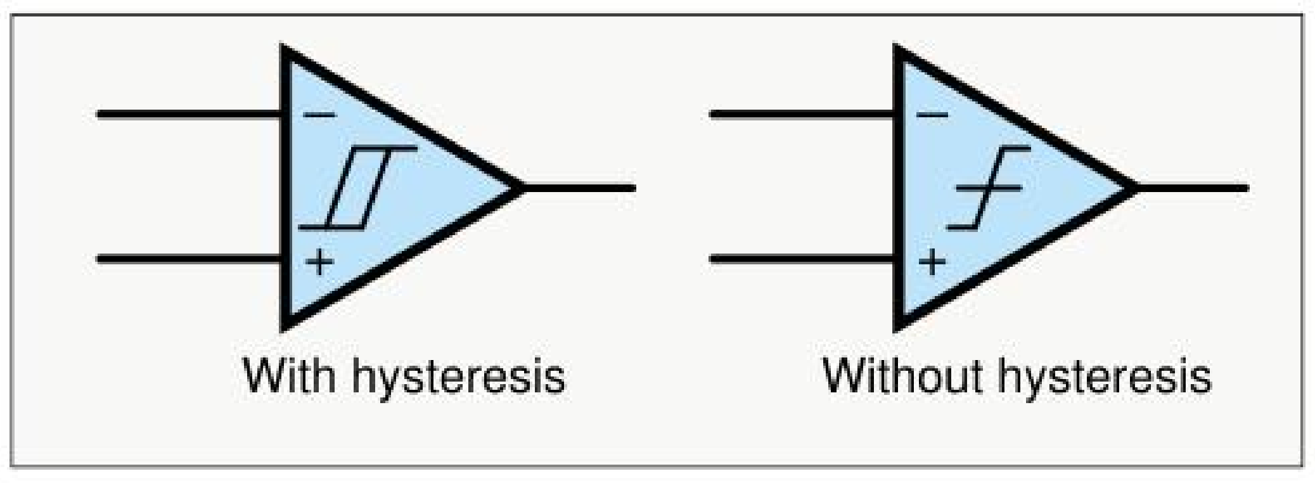

–
+
With hysteresis
–
+
Without hysteresis

Fig.10. Alternative comparator symbols.

A comparator with hysteresis can be made using a single simple comparator by setting the threshold (reference voltage) depending on the comparator's current output state. The comparator has two output states (two possible output voltages V_{OL} and V_{OH}), which set the two thresholds. This arrangement uses positive feedback – the output voltage is fed back to shift the threshold. If the input noise level is known, then the hysteresis can be set slightly larger than this. The comparator will then not switch (or very rarely switch) as a result of the noise.

Some comparators have built-in hysteresis (for example 500µV for AD790), otherwise hysteresis can be added using external resistors. We will discuss the design of these circuits in detail (operation component value calculation) after comparing the behaviour of a comparator, with and without hysteresis, using a simulation. Although comparators are often shown in schematics using the symbol in Fig.1, the more specific symbols shown in Fig.10 can also be used. These distinguish comparators from op amps and indicate if there is built in hysteresis or not.

Fig.11. LTspice simulation schematic to show the difference between circuits with and without hysteresis.

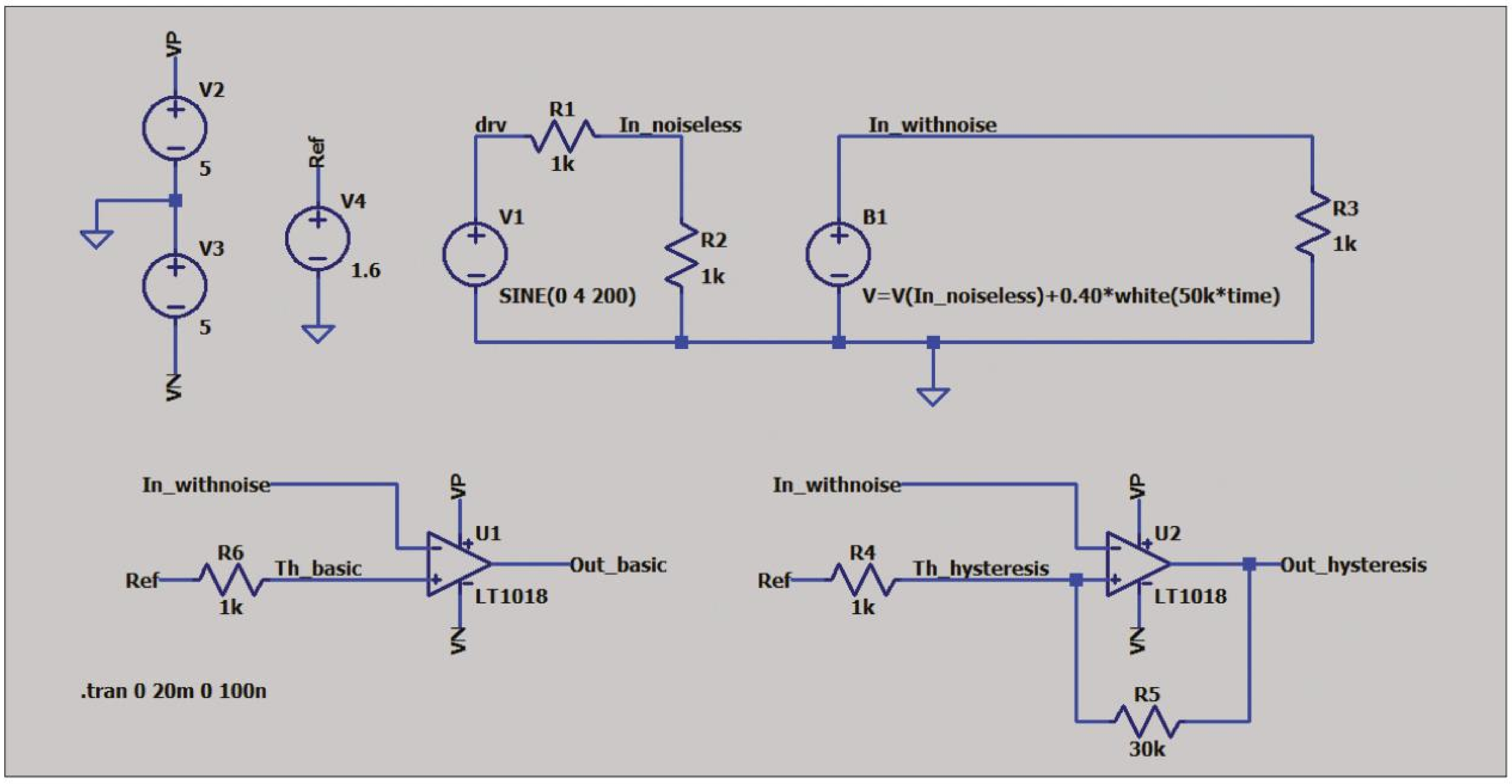
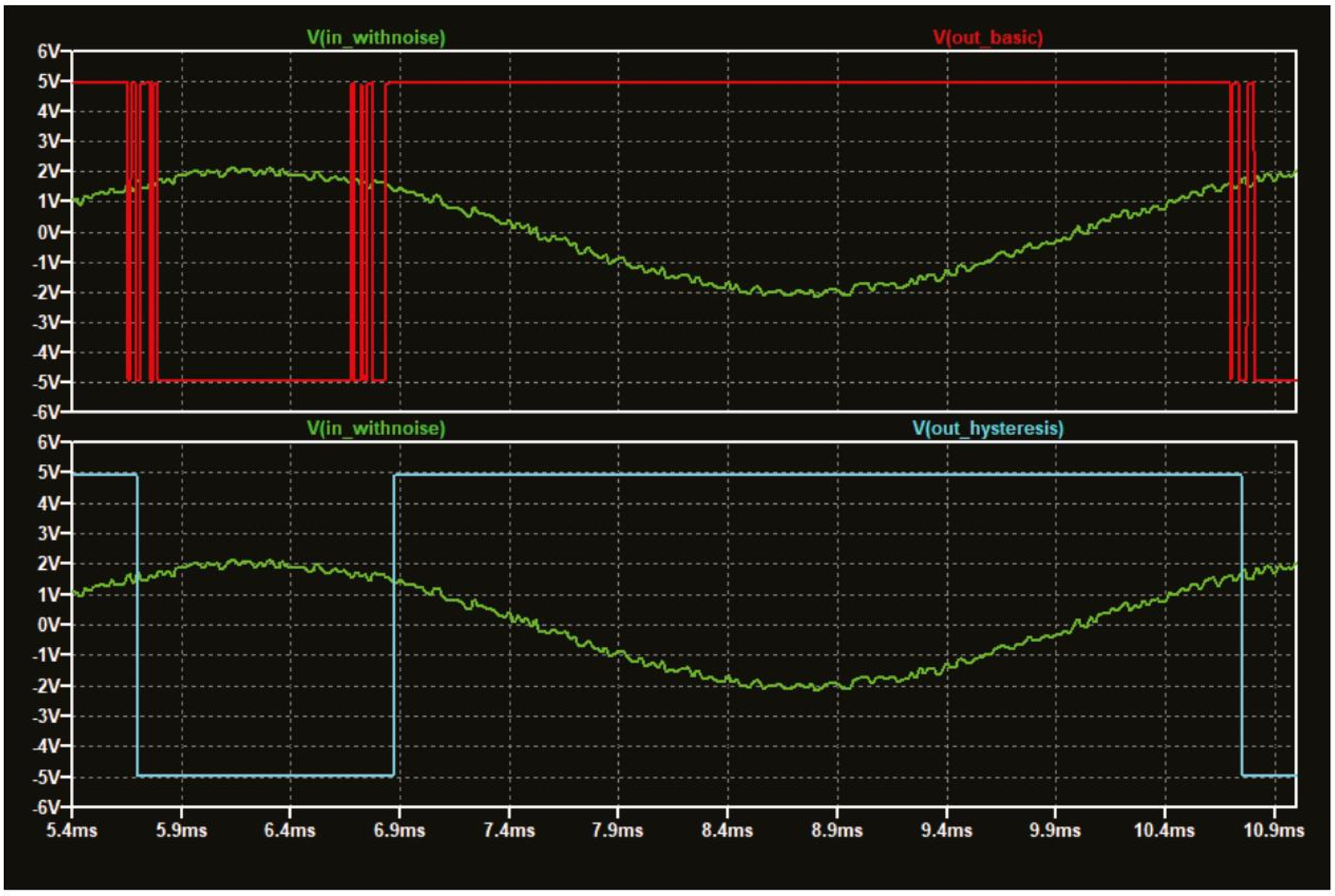

VP
V2
5
V3
5
VN
Ref
V4
1.6
drv
R1
1k
In_noiseless
V1
SINE(0 4 200)
R2
1k
In_withnoise
B1
V=V(In_noiseless)+0.40*white(50k*time)
R3
1k
In_withnoise
Ref
R6
1k
Th_basic
VP
U1
LT1018
VN
Out_basic
In_withnoise
Ref
R4
1k
Th_hysteresis
VP
U2
LT1018
VN
Out_hysteresis
R5
30k
.tran 0 20m 0 100n

Fig.12. Response of the two comparators from the simulation schematic in Fig.11. The upper plot pane shows a basic comparator switching multiple times as the threshold is crossed. The lower plot pane shows that use of hysteresis cleans up the switching.



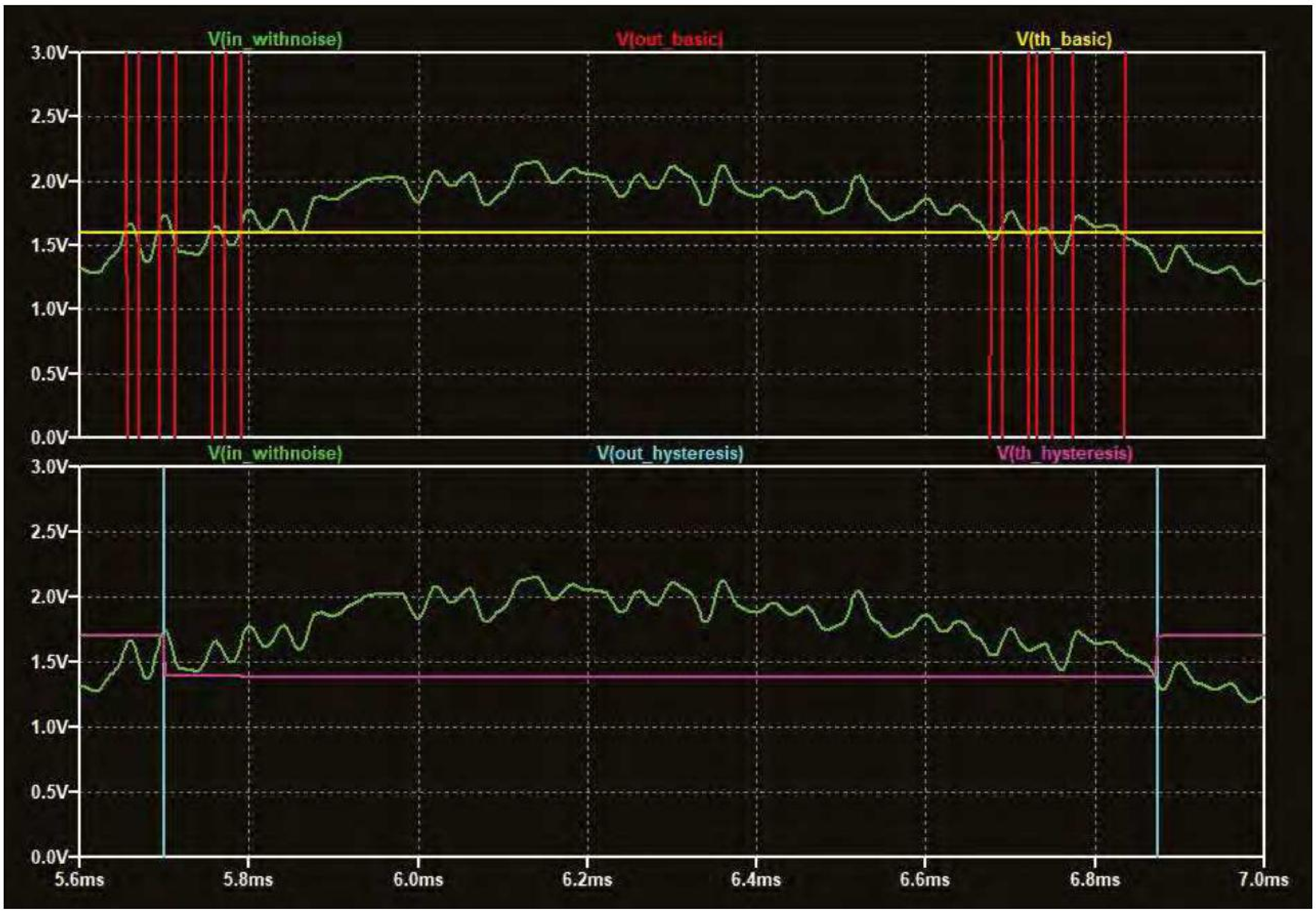


Fig.13. A zoom in on two of the threshold crossings from Fig.11 to show the waveform at the switching point in more detail. The threshold voltages are also shown. The change in the threshold for the hysteresis comparator can be seen in the lower plot pane (magenta trace).

Hysteresis comparison simulation

Fig.11 shows an LTspice simulation schematic for comparing comparator circuits with and without hysteresis. The circuit uses the LT1018 to implement two inverting comparators. The LT1018 has an internal pull-up in its output stage – it supports wired logic but does not need an external pull-up resistor.

`U1` is used as a basic comparator without hysteresis. The input voltage is compared to the voltage on the positive input of the comparator (node `Th_basic`) – the switching threshold. This voltage will be very close to reference voltage $V_{\mathbf{ref}}$, supplied by `V4` (voltage on node `Ref`, 1.6V). It will change if the input bias current of the comparator changes, but the headline figure for bias current for the LT1018 is 15nA, corresponding with a 15µV drop across `R6`, and any changes when the device switches are likely to be smaller than this. Thus, the voltage on `Th_basic` is effectively constant.

`U2` is configured as a comparator with hysteresis using positive feedback via `R5` (and `R4`). At first glance, the circuit might look like an op amp amplifier, but note the feedback is to the positive (non-inverting) input terminal. The input voltage is compared to the voltage on the positive input of the comparator (node `Th_hysteresis`). Due to the feedback, this threshold voltage will change significantly when the output voltage of the comparator changes.

The simulation creates a $4.0V_{\text{pk-pk}}$, 200Hz sinewave on node `in_noiseless` using voltage source `V1`. A randomly varying voltage of up to $0.4V_{\text{pk-pk}}$ is added to the sinewave using behavioural voltage source `B1` with expression:

```
V=V(In_noiseless)+0.40*white(50k*time)
```

The random values are provided by the LTspice mathematic operation `white(x)`, which generates a random number between –0.5 and 0.5 and smoothly transitions between values. The value of `white(x)` changes with each integer value of x. The value used here (`50k*time`) changes to a new integer every 20µs of simulation time. It approximates random noise on the 200Hz sinewave.

Fig.12 and Fig.13 show the result of applying the same noisy signal to a basic comparator (the circuit using `U1` in Fig.11) and one with hysteresis (the `U2` circuit). The basic comparator switches multiple times as the noisy signal crosses the threshold, whereas the comparator with hysteresis switches cleanly. Fig.12 shows that the behaviour of the basic comparator as it switches is different each time due to the random nature of the noise.

Fig.13 shows more detail for one threshold crossing and includes plots of the threshold voltages. For the basic comparator, the threshold (`Th_basic`) remains constant – it actually changes by about 6µV when the compactor switches, but this is far too small to see on the scale plotted. For the comparator with hysteresis, the threshold voltage (`Th_hysteresis`) changes by about 320mV when the comparator switches – this is of the same order as the noise amplitude.

Circuit design

Fig.14 shows an inverting comparator with hysteresis – the same configuration as in Fig.11. Since the thresholds depend on the comparator's output voltages these should ideally be accurately defined. For push-pull outputs this should not be a problem (outputs equal to the supplies), but where pull-up resistors are used these may need to be included in the design calculations. We will assume that output voltages are well defined in the following discussion.

The circuit in Fig.14 uses an external reference voltage (V_{ref}) to help set the thresholds. We assume V_{ref} is from a voltage source with a low source resistance compared to R_1, or that R_1 is the source resistance and that it is of a known and fixed value.

The switching point V_{comp} depends on V_{ref} and V_{out}. V_{ref} will usually be fixed but V_{out} depends on the current state of the comparator. V_{out} can take one of two values, which we will assume to be $\pm V_O$ (the positive and negative outputs apply to split-supply circuits). Initially, let us assume that $V_{\text{in}} < V_{\text{comp}}$ so $V_{\text{out}} = +V_O$. If V_{in} is slowly increased this condition remains until $V_{\text{in}} = V_{\text{comp}} = V_{\text{TH}}$ (see Fig.9), where:

$$V_{TH} = \frac{R_2}{R_1 + R_2} V_{ref} + \frac{R_1}{R_1 + R_2} V_O$$

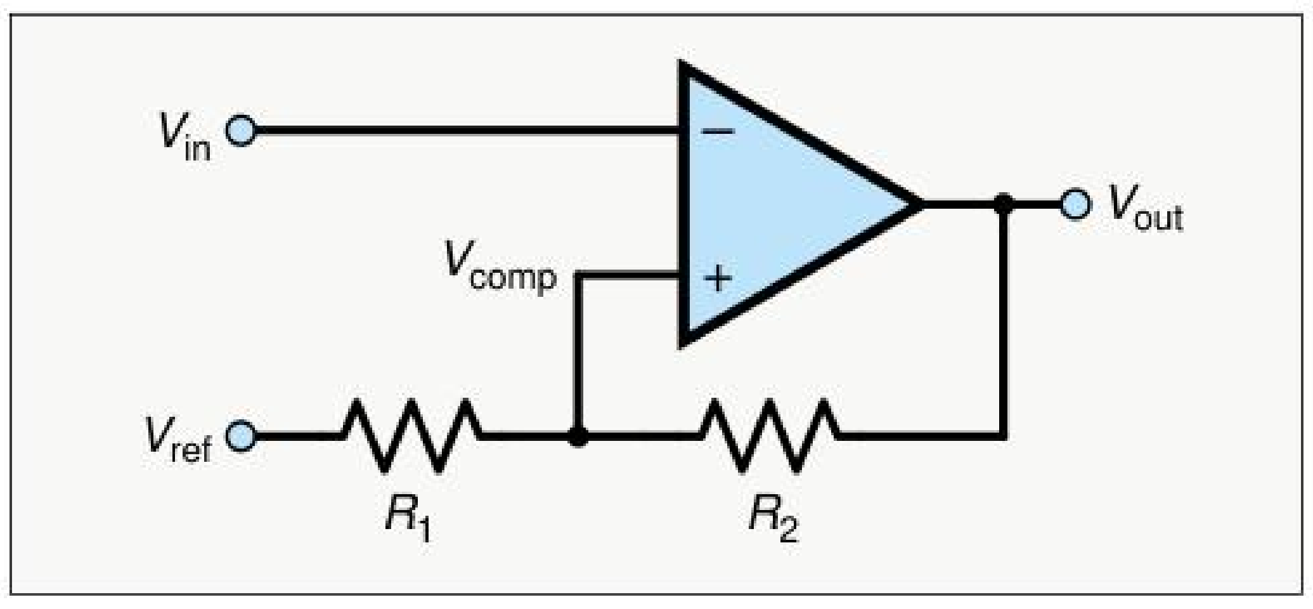


Fig.14. Inverting comparator with hysteresis.

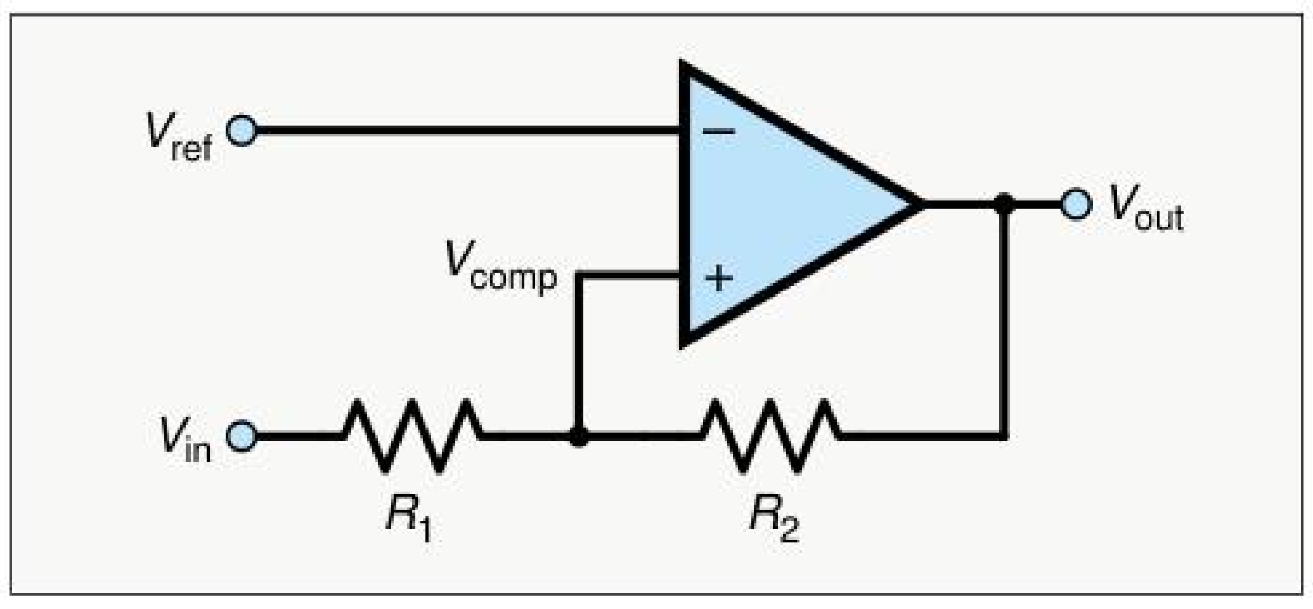


Fig.15. Non-inverting comparator with hysteresis.

This equation is obtained by applying the potential divider equation twice and adding the results. First to find the contribution of V_{ref} to V_{comp} with $V_{out} = 0$ and then to find the contribution of V_{out} to V_{comp} with $V_{ref} = 0$. This is an application of the circuit theory superposition theorem.

On switching at $V_{comp} = V_{TH}$ the output changes to $V_{out} = -V_O$, changing the switching point to a new value, $V_{comp} = V_{TL}$:

$$V_{TL} = \frac{R_2}{R_1 + R_2}V_{ref} - \frac{R_1}{R_1 + R_2}V_O$$

This is calculated in the same way as V_{TH} but with $V_{out} = -V_O$. V_{out} will now stay at $-V_O$ until the input falls below V_{comp} again. The difference in the switching points – the hysteresis, V_H – is given by:

$$V_H = V_{TH} - V_{TL} = \frac{2R_1}{R_1 + R_2}V_O$$

The switching is symmetrical about the average of V_{TH} and V_{TL}, which is:

$$\frac{R_2}{R_1 + R_2}V_{ref}$$

If R_2 is much larger than R_1 (which is not unusual), the average of V_{TH} and V_{TL} is approximately equal to V_{ref}. Under these conditions the comparator switches at points $V_H/2$ above and below V_{ref}. For the circuit in Fig.11, the switching points are 1.548 ±0.161V (1.71V and 1.39 V) – note that this is not centred exactly on the 1.6V reference.

If the comparator is run from a single supply the output (ideally) switches between $+V_O$ and 0 rather than $+V_O$ and $-V_O$. The formula for V_{TH} is the same, but the zero removes the $-V_O$ term from the V_{TL} equation, so it becomes:

$$V_{TL} = \frac{R_2}{R_1 + R_2}V_{ref}$$

If R_2 is much larger than R_1 the lower threshold (V_{TL}) is close to V_{ref}, rather than V_{ref} being approximately at the centre between the two thresholds, as it is with the split supply circuit. This may be a source of confusion with single-supply circuits.

Non-inverting comparator

The non-inverting comparator with hysteresis is shown in Fig.15 – we just swap the input and reference. The analysis proceeds in a similar way, noting that the comparator always switches at $V_{comp} = V_{ref}$, the relationship of V_{comp} to V_{in} changes with the value of V_O, and, by definition, $V_{in} = V_{TH}$ or $V_{in} = V_{TL}$ at the two thresholds. So, for the higher threshold, using superposition with the potential divider formulae, as before, we get (with split supplies):

$$V_{comp} = V_{ref} = \frac{R_2}{R_1 + R_2}V_{TH} - \frac{R_1}{R_1 + R_2}V_O$$

Rearranging, to make V_{TH} the subject:

$$V_{TH} = \frac{R_1 + R_2}{R_2}V_{Ref} + \frac{R_1}{R_2}V_O$$

Similarly:

$$V_{TL} = \frac{R_1 + R_2}{R_2}V_{Ref} - \frac{R_1}{R_2}V_O$$

We can use $V_O = 0$ in the V_{TH} formula for a single-supply version.

Potential dividers

V_{ref} for the circuits in Fig.14 and Fig.15 can be obtained from a potential divider connected between the supplies. Ideally, to prevent the threshold-setting network loading the potential divider and influencing the reference voltage, the potential divider resistors would need to have relatively low resistance. A better approach is to actually use the interaction between a potential divider and feedback resistor to set the two threshold voltages using the circuit shown in Fig.16.

For a single-supply circuit (as in Fig.16) the comparator's output voltage is either $+V_O$ or 0. When the comparator output is 0V, R_3 is effectively connected to ground in parallel with R_1. The parallel value of these resistors (R_{P13}) is, using the formula for two parallel resistors:

$$R_{P13} = \frac{R_1 R_3}{R_1 + R_3}$$

This resistance forms a potential divider with R_2 to set the lower threshold:

$$V_{TL} = \frac{R_{P13}}{R_{P13} + R_2}V_O$$

When the comparator output is V_O, R_3 is effectively connected to the supply in parallel with R_2. The parallel value of these resistors (R_{P23}) is:

$$R_{P23} = \frac{R_2 R_3}{R_2 + R_3}$$

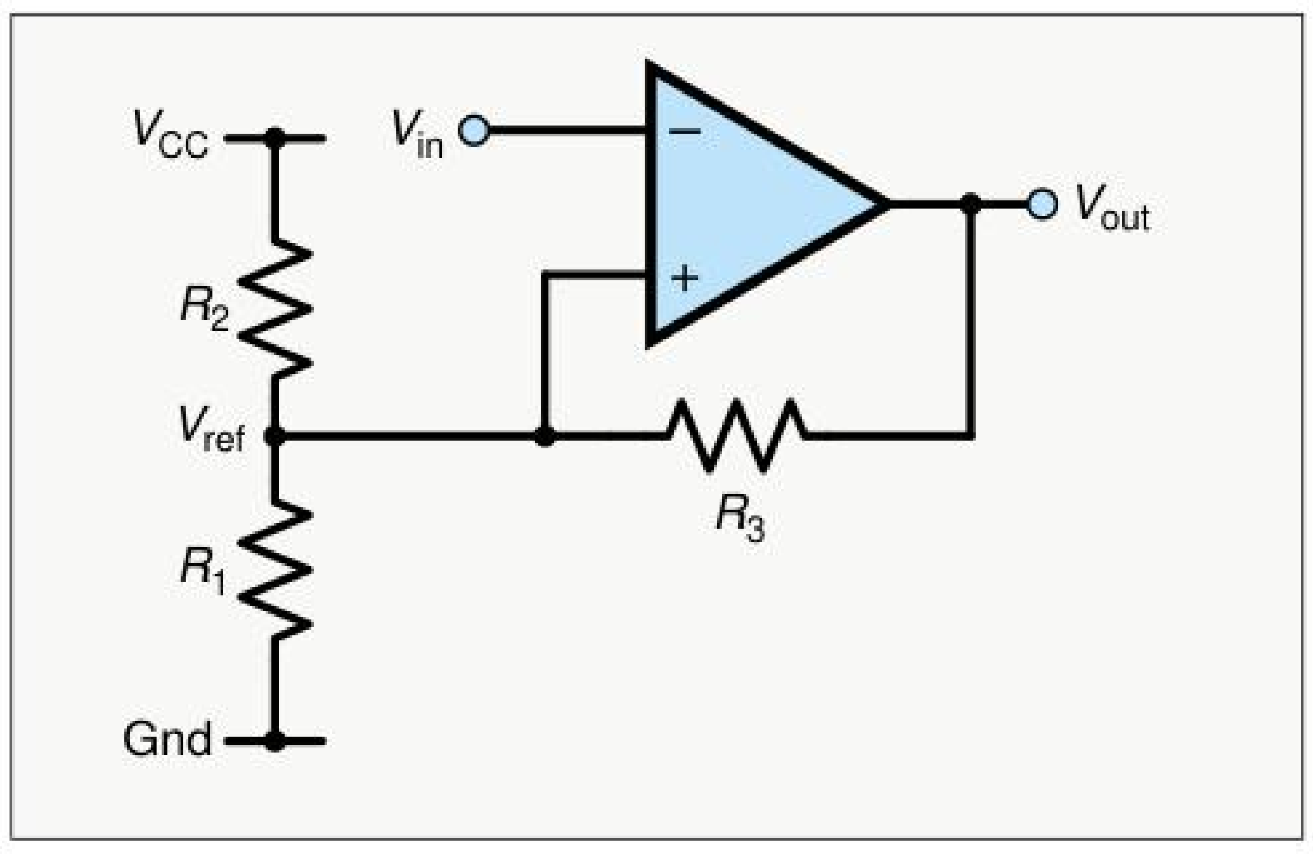


Fig.16. A potential divider can be used in conjunction with a feedback resistor to set comparator thresholds – single-supply circuit shown.

This resistance forms a potential divider with R_1 to set the upper threshold:

$$V_{TH} = \frac{R_1}{R_1 + R_{P23}}V_O$$

The switching points for the circuit in Fig.16 are not necessarily symmetrical around the open circuit voltage of the R_1, R_2 potential divider. For example, if we have $V_O = 5V$ and choose $R_1 = 5kΩ$ and $R_2 = 25kΩ$ we get a potential divider voltage of 833mV, with nothing else connected to it. If we have a feedback resistor $R_3 = 100kΩ$ then R_{P13} is 4.762kΩ, R_{P23} is 20kΩ and the threshold voltages are $V_{TL} = 0.800V$ and V_{TH}, = 1.00V (using the above formula). We have a total hysteresis of 200mV, but the lower threshold (in this example) is much closer to the open-circuit potential divider voltage than the upper threshold.

As noted above, use of comparators with pull-up resistors may affect the accuracy of the above formula. This will tend to happen if the pull-up resistor (R_{PU}) is not much smaller than the feedback resistor. Under these conditions the formulae can be adjusted to use the sum of the feedback and pull-up resistors, instead of just the feedback resistor value, where relevant. For example, for the non-inverting comparator (Fig.15):

$$V_{TL} = \frac{R_1 + R_2 + R_{PU}}{R_2 + R_{PU}}V_{Ref} - \frac{R_1}{R_2 + R_{PU}}V_O$$

Finally, in common with many circuits, comparators often require good supply decoupling close to the device, particularly when fast switching is required. Datasheets will often provide advice on decoupling requirements.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*. The examples and files are available for download from the *PE* website.

Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 47: A PicoMite Smart-light Controller – Part 2

Last month, we introduced the concept of a *Smart-light Controller* specifically for controlling the Philips Hue range of lighting products. There are two main reasons for selecting the Philips Hue range – first, Philips provide documentation which explains how to interface to their hardware to control it with simple commands; and second, the quality and reliability of the Hue range is excellent (but noting it is more costly than most other manufacturers).

The heart of any Philips Hue smart-home setup is the Hue Hub (see Fig.1). Philips have incorporated an API (application programming interface) into their Hub, which means it is possible to communicate with it using a standard web protocol (more on this later). For this to work, the Hue Hub needs to be plugged into your home network; and this is typically done by connecting it to your Wi-Fi router. The Hue Hub then appears as a device on your network, meaning it will have an IP address for communication purposes.

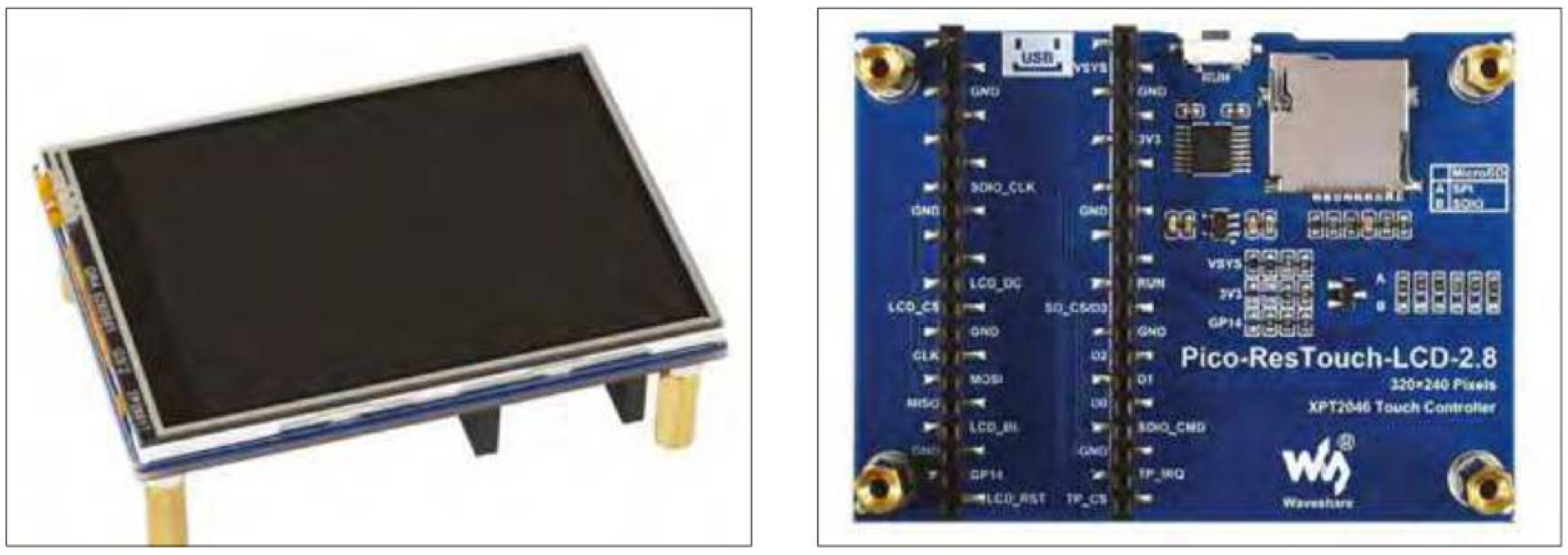


Fig.2. The Waveshare Pico-ResTouch-LCD-2.8 module is an ideal touchscreen for use in our *Smart-light Controller*. It connects directly with the PicoMite – no cables needed. It also has an onboard SD socket which may prove useful.

Fig.1. The Philips Hue Hub is the heart of a Hue setup. When connected to your home network it acts as an 'Internet gateway', allowing you to use the Hue App to control all your Hue smart lights (and smart sockets) from anywhere with an Internet connection.

Put simply, by sending specific commands via Wi-Fi to the Hue Hub API, we can let it know how we want to adjust the smart lights. The Hue Hub will then take care of the more complex Zigbee protocol that Philips uses to communicate directly with Hue smart lights (and other Hue accessories).

If you already have one or more Hue products, you will most likely have also downloaded the Philips Hue App onto a smart phone or tablet. This App provides complete control of any Hue product in your setup, and it can do this because it sends the relevant commands via your Wi-Fi network directly to the Hub's API.

So, all our PicoMite *Smart-light Controller* needs to do is communicate with the Philips Hue Hub in a similar way to the Hue App; something which is well documented by Philips.

Therefore, this month we explain how to prepare the Hue Hub so that we can communicate with it; plus, we will assemble a test circuit to ensure we can indeed control a Hue smart light. Let's start by looking at what PicoMite hardware will be used in our *Smart-light Controller*.

PicoMite hardware

From a hardware point of view, our controller will comprise the following three elements:

1. ESP32 Wi-Fi module – provides communication ability with the Hue Hub via Wi-Fi
2. Touchscreen – for our graphical user interface (GUI)
3. PicoMite – the 'brains' of our controller.

Last month, in *Part 1* of this project, we covered how to upgrade the firmware inside an ESP32 so that we have access to all the relevant commands that will be used in our program code. As a brief reminder, we will be sending `AT` commands from the PicoMite to the ESP32 to control all aspects relating to Wi-Fi network communication with the Hue Hub. Remember to ensure the ESP32 firmware has been updated – as described in *Part 46* – before connecting it up.

For the Touchscreen, you can use any compatible one that you have at hand. Here, we will use the readily available Waveshare Pico-ResTouch-LCD-2.8 module (see Fig.2). This is an SPI touchscreen with an SD socket, which may prove useful.

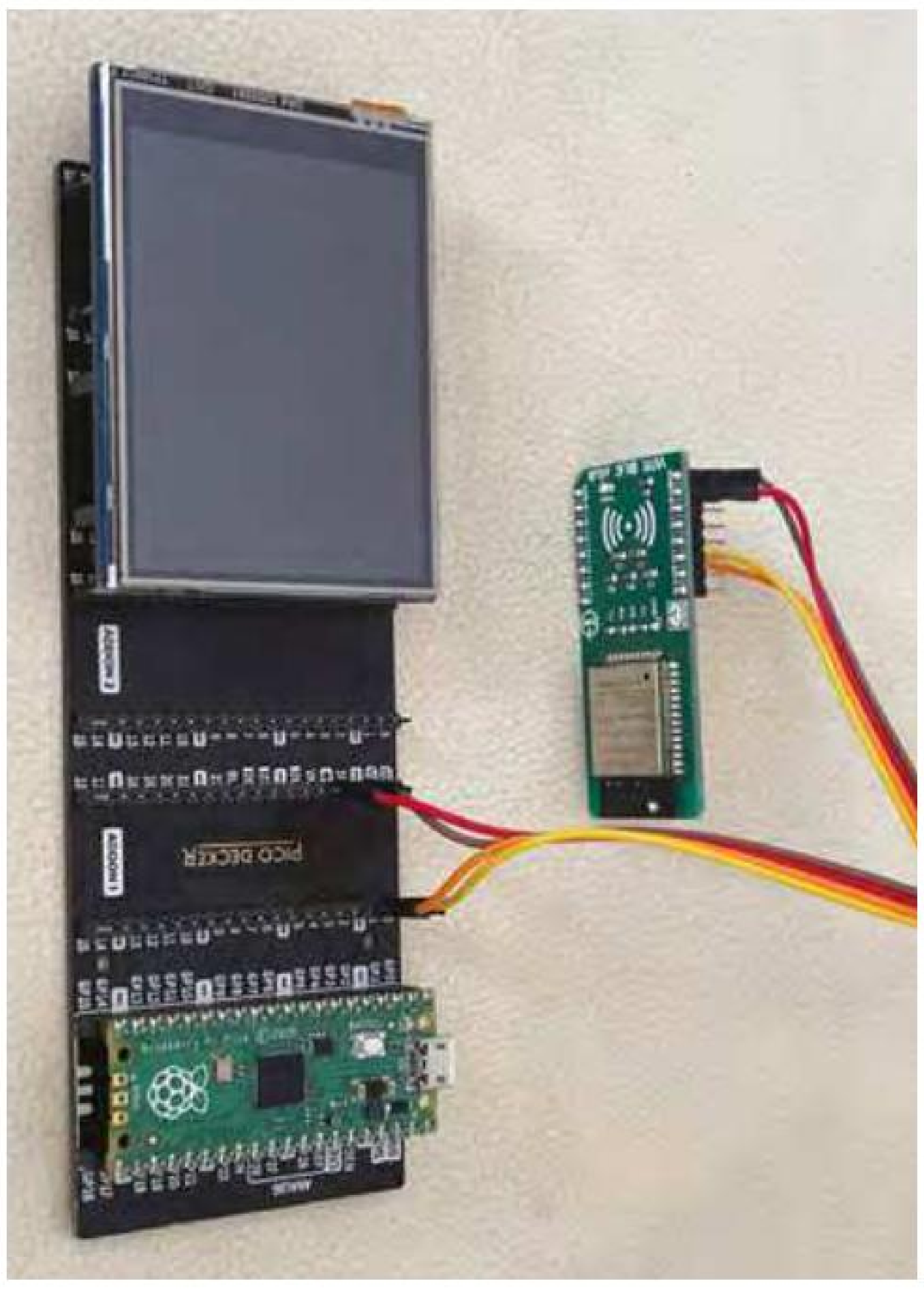


Fig.3. A Pico expansion module like the one shown here makes it much easier to assemble our test circuit. Just four female-female DuPont leads are needed to hook up the ESP32 module.

It is a plug-and-play device that needs no cables to connect it to the PicoMite.

For test purposes, we recommend plugging these three modules into a Pico Expansion module (see Fig.3). The PicoMite and the Touchscreen can be mounted directly onto the expansion module; however, for the ESP32 module, simply use four DuPont leads to connect it to the PicoMite – see Fig.4 for the relevant pin numbers.

One more consideration at this stage is to ensure that you have the latest version of the PicoMite firmware installed on your PicoMite. Visit **geoffg.net/picomite.html** and scroll to the Downloads section at the bottom of the page to obtain the latest **.uf2** file (at the time of writing it was **PicoMiteV5.07.06.uf2**). A zipped folder will be downloaded, so you will need to extract it after downloading; and the required **.uf2** file will be one of several files contained within the extracted folder. Here's a reminder of how to install the downloaded **.uf2** file into the PicoMite using the following three steps:

1. Plug the Raspberry Pi Pico into your computer with a USB cable, while holding down the white BOOTSEL button on the Raspberry Pi Pico. The Pico should connect to your computer and create a virtual drive (as if you had plugged in a USB memory stick). This virtual drive will contain two files which you can ignore (but do not delete them!).
2. Copy firmware file **PicoMiteV5.07.06.uf2** to this virtual drive.
3. When the copy is completed, the Pico will restart and create a virtual serial port on your computer. The LED on the Pico will blink slowly, indicating that the PicoMite firmware with MMBasic is now running.

The Firmware update should take no more than a couple of minutes and will ensure you have access to the MMBASIC commands we will use in our final program code.

Checking the test circuit

With everything connected, the next step is to ensure that you have the relevant `OPTION`s configured. The exact ones required will depend on the touchscreen that you use, but for the display module we're using here (Waveshare Pico-ResTouch-LCD-2.8) the `OPTION`s are:

```
OPTION SYSTEM SPI GP10,GP11,GP12
OPTION CPUSPEED (KHz) 252000
OPTION LCDPANEL ST7789_320,
LANDSCAPE,GP8,GP15,GP9,GP13
OPTION TOUCH GP16,GP17
OPTION SDCARD GP22
```

Now set the relevant `OPTION`s, remembering to calibrate the touchscreen if required (with the `GUI CALIBRATE` command). It is also worth performing a quick test of the touchscreen using the usual commands `GUI TEST LCDPANEL` and `GUI TEST TOUCH`. If it doesn't work as expected, then quickly check that the touchscreen is inserted correctly into the Pico Expansion module, and then check the parameters used in each of the `OPTION` commands (use `OPTION LIST` to display them). Correct any errors you see – you may need to use the `OPTION…DISABLE` command. Once the touchscreen is confirmed as working correctly, download and install the first test program – **SmartLightController_Test1.txt** – available for download from the June 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

This simple test program will first attempt to connect to your Wi-Fi network, and then it will attempt to fetch the current date and time from an Internet time server (and display the date and time on the touchscreen). However, before you `RUN` the program, you first need to modify two lines of code. These need to be changed so that the program code can send your Wi-Fi network name (SSID) and your Wi-Fi password to the ESP32, which will then allow it to connect to your Wi-Fi network.

To do this, go to the editor (`EDIT`) and scroll down to the first two lines of uncommented code in the SETUP section. Here you will see the two required string variables (`SSID$` and `PWD$`) that need to be modified. Edit them to contain the SSID and the password of your Wi-Fi network. Once this is done, `RUN` the program and observe your terminal app's screen to see what is happening. After a short while, the current date and time should be displayed on the touchscreen. If the date or time is clearly incorrect (for example, 'Thu Jan 1 1970 01:00:10'), simply wait a short while and `RUN` the program again. Any errors observed on the terminal screen will likely be caused by an incorrect SSID or password being used. Also, do ensure that you have access to the Internet on your Wi-Fi network. If you don't have Internet access, then the ESP32 will be able to connect to your Wi-Fi network (when the correct SSID and password are used), but it won't be able to connect to an Internet time server to display the correct date and time.

Note that it will not be a requirement to have Internet access for our *Smart-light Controller* as it will only need to communicate directly with the Hue Hub (which is simply a device on your home network). However, the likelihood is that you will also have Internet access, and hence this test program checks that too by linking to an Internet time server.

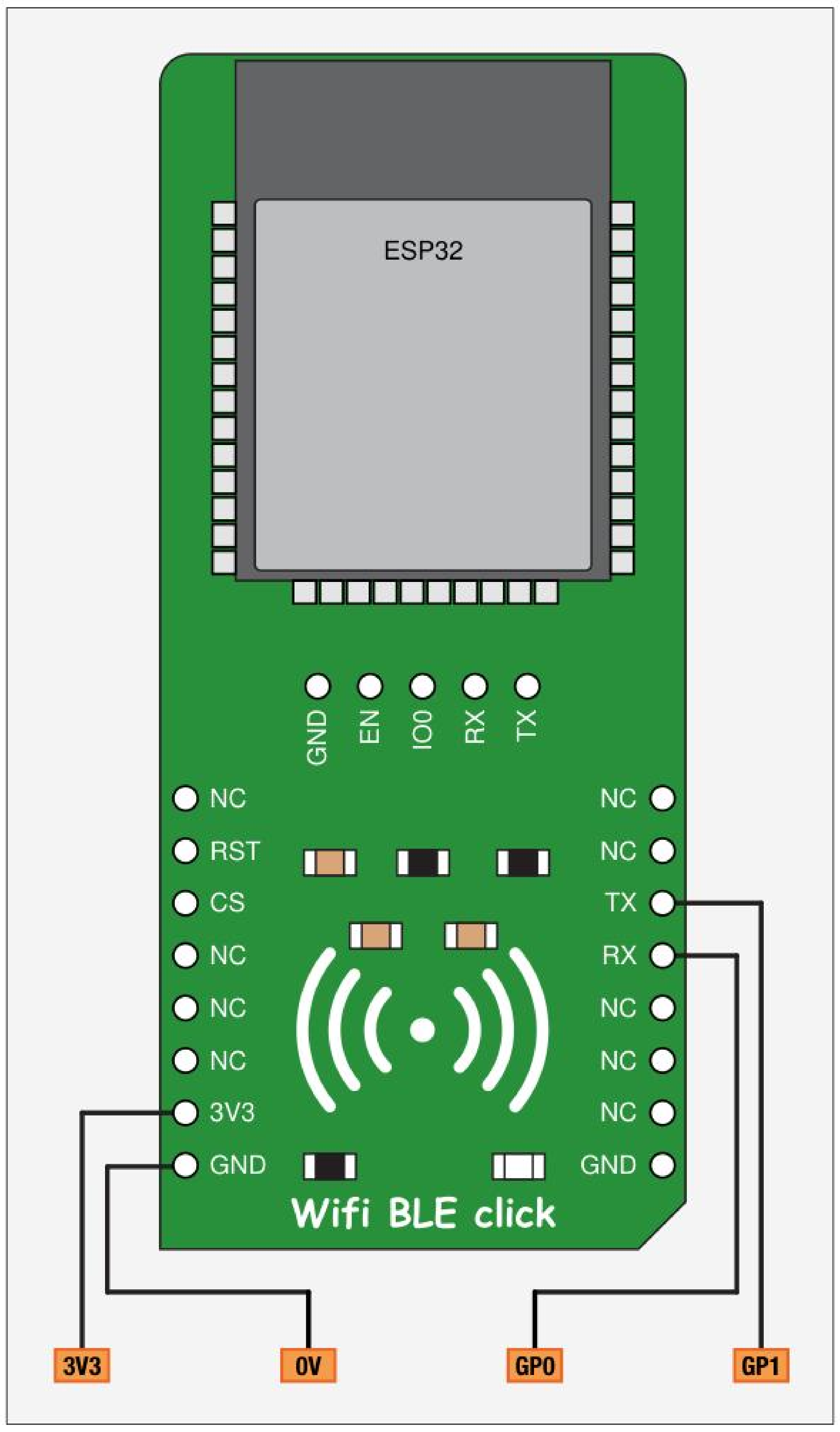


Fig.4. Only four connections are needed to connect the ESP32 module to the PicoMite. Two are for the 3V3 power supply (do *not* connect to 5V!); and two for the serial Tx and Rx signals.

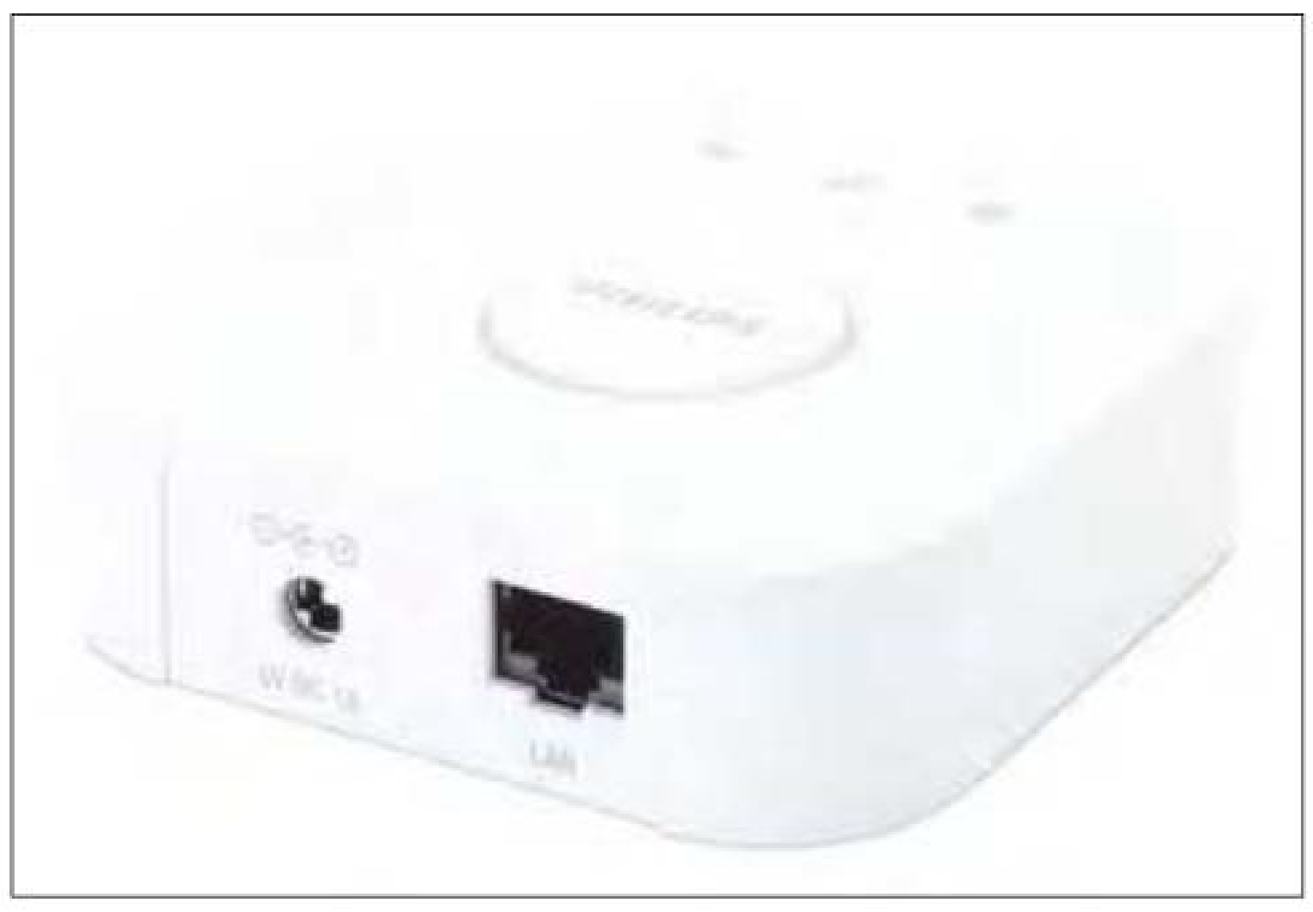


Fig.5. The Hue Hub is easy to install – just two leads connect to the rear of the Hub for power and to your network (ie, Wi-Fi router).

It must be stressed that it is not important at this stage to understand how the code works – it is just being used for checking the test circuit. With a test circuit built and successfully checked, we can now turn our attention to the components in the Hue setup.

Configuring the Hue system

To prepare the Hue components for receiving communication from our Smart-light Controller, complete the following steps:

1. Install the Hue Hub (on your network)
2. Install the Hue App (on a smart phone or tablet)
3. Configure the Hue Hub (as per instructions from Philips)
4. Install and configure at least one Hue smart light so we have something for our controller to control
5. Identify the IP address of the Hue Hub, and make it 'Static' so that we know the IP address that our controller will need to communicate with
6. Obtain a unique API key from the Hue Hub (required for security reasons to prevent hackers controlling our lights)
7. Get a list of smart light IDs from the Hue Hub so we can tell the Hue API which specific light ID we are controlling.

If you already have a Hue setup (with a Hue Hub), then the first four steps can be skipped; however, if you're just starting out with Hue, then all seven steps will need to be performed. Once the required steps have been completed and we have the relevant information, we will then be able to use our test circuit from above to check that we can indeed control one of the smart lights in the setup. Please note that without the IP address of the Hub, or the API key, or the relevant smart light ID, or the appropriate command instruction, our *Smart-light Controller* will not work.

Do not panic if any of these steps don't make sense at this stage – the list above is just provided as an overview of what we will be discussing in the next few sections. By the end of this article, everything will become clear.

1. Install the Hue Hub

This is a straightforward step. When you purchase a Hue Hub (around £50 if purchased by itself, or cheaper if purchased in a Hue kit), there are three main items in the box: the Hub (also referred to as a 'Hue Bridge'), its power supply and a network lead. At the back of the Hue Hub you will see two sockets (Fig.5). First connect the Hue Hub to your Wi-Fi router with the supplied network lead, and then connect the power supply. The blue LEDs will start to turn on, and after a short while, all three on the top should be lit. These LEDs (from right-to-left) indicate Power, Wi-Fi connection, and Internet connection. That's it, the Hue Hub is installed. We will configure it in Step 3 after the Hue App has been installed.

2. Install the Hue App

The Hue App is required to configure the Hue Hub; and is also used to add smart

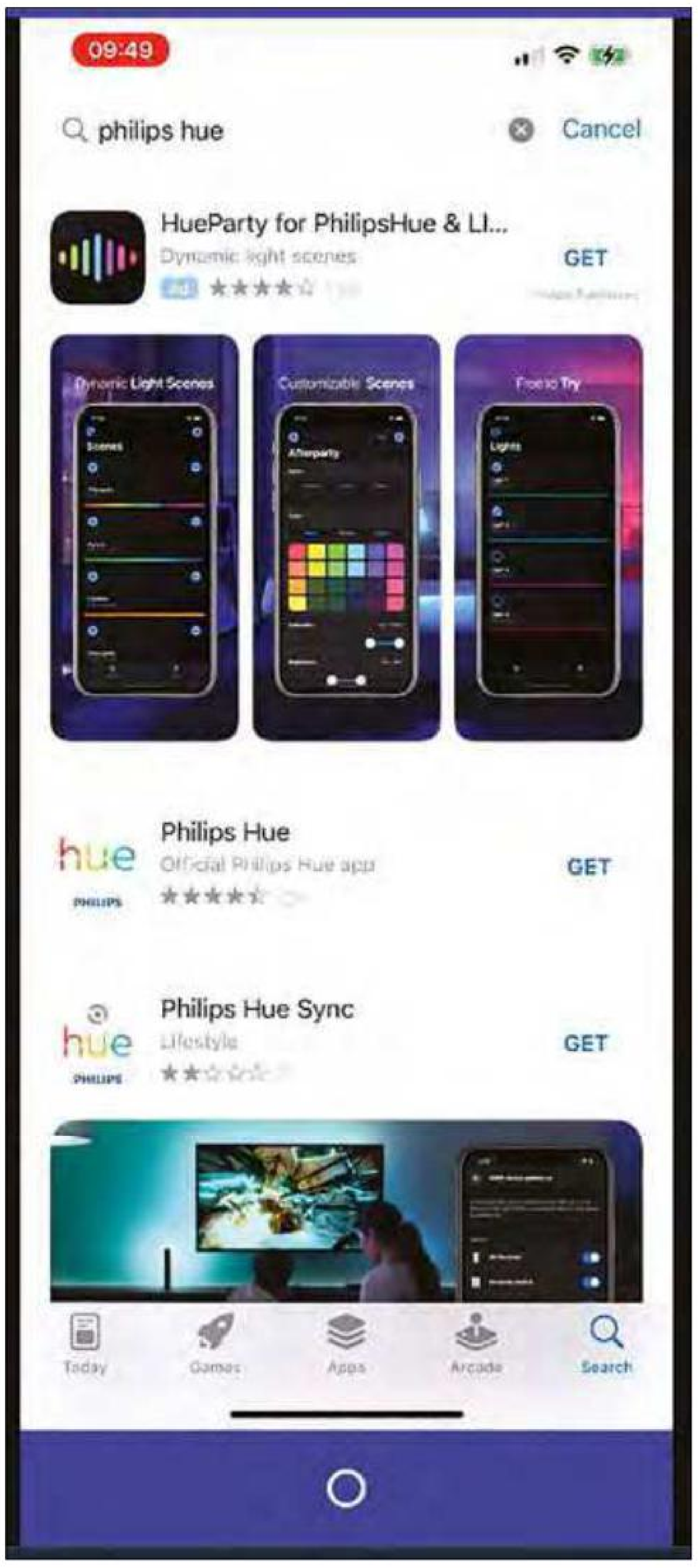
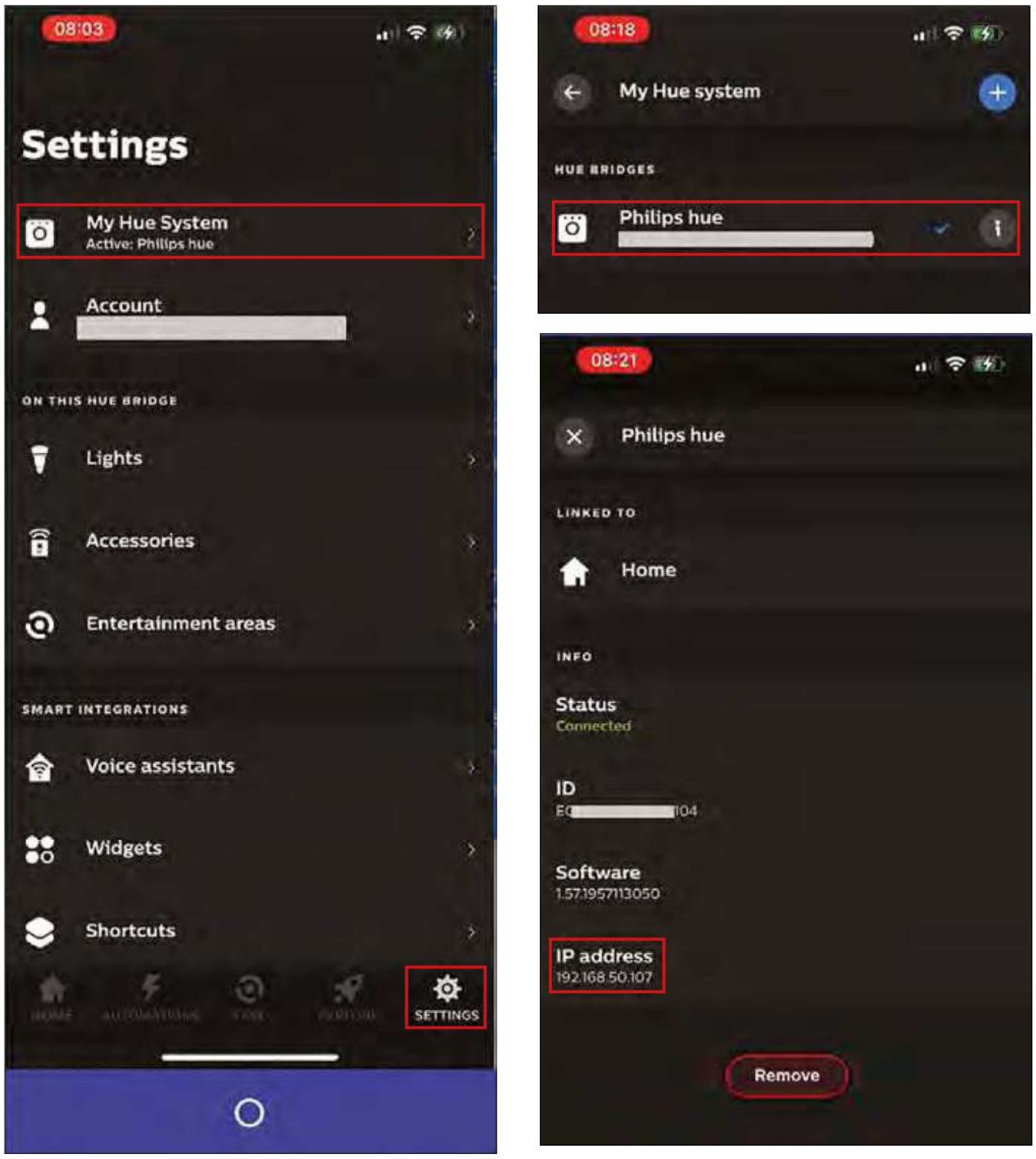

09:49
philips hue
Cancel
HueParty for PhilipsHue & Li...
Dynamic light scenes
GET
Dynamic Light Scenes
Customizable Scenes
Free to Try
Philips Hue
Official Philips Hue app
GET
Philips Hue Sync
Lifestyle
GET
Today
Games
Apps
Arcade
Search

Fig.6. There are many Apps related to Hue. Be sure to download the official Philips Hue App.


08:03
Settings
My Hue System
Active: Philips hue
Account
ON THIS HUE BRIDGE
Lights
Accessories
Entertainment areas
SMART INTEGRATIONS
Voice assistants
Widgets
Shortcuts
SETTINGS
08:18
My Hue system
HUE BRIDGES
Philips hue
08:21
Philips hue
LINKED TO
Home
INFO
Remove

Account [redacted]

Philips hue [redacted]

Status
Connected

ID
EC[redacted]104

Software
1.57.1957113050

IP address
192.168.50.107

Fig.7. a) (left) To find the IP address of the Hub, select 'My Hue System' from the 'Settings' page in the Hue App; b) (top right) tap the 'i' icon; and c) (bottom right) The Hub's IP address will then be displayed.

lights and other smart devices such as switches, buttons, sockets and movement sensors. It can also be used to control any device in your setup (ie, turn a light on or off), and is particularly useful for device control when you're away from home.

The Hue App is free and available for download from the Google Play Store (for Android devices) and from the App Store (for Apple iOS devices). Search for 'Philips Hue' and you will see many Apps available. Be sure to install the 'Official Philips Hue app' which is simply called 'Philips Hue' (see Fig.6). After a few seconds it will be installed. Next, open it, to configure the Hue Hub.

3. Configure the Hue Hub

When the Hue App is run for the first time, it will want to search for a Hue Hub (although there are a few confirmation buttons you will need to press first). We will not go into step-by-step detail here as Philips have made the process pretty much idiot-proof from the App! You will essentially have to press the round button on top of the Hue Hub (when instructed to do so), and the App will automatically link to it. It will then want to run a software update for the Hue Hub – let this update complete and wait for the confirmation message showing that your Hue Bridge is up to date.

The App will then go to the Home page from where you 'add a room' by clicking the three dots in the top-right corner (and select the option 'Add a new Room or Zone'). By adding an appropriately named room you will have somewhere to place the smart light that we'll be adding in the next step. I find the Hue App very intuitive, however, if you do struggle with adding a room, or with anything else regarding the Hue App, then turn to the Internet where there are many step-by-step videos and tutorials.

4. Install and Configure at least one Hue smart light

To add a Hue smart light to the setup, you simply click the three dots in the top-right corner of the Home page and select 'Add lights'. You will then see an option to 'Search', but before you do this you must ensure the Hue smart light is installed in the light fitting and that it has power too – this means the smart light will initially be turned on. Upon pressing the Search button, the App will look for your new smart light, and after a few seconds, will display it in the App. Note that if you purchased a Hue kit, then the lights may already be shown in the App, meaning you can bypass the Search function.

Once the smart light is listed in the App, you can rename it to something meaningful (eg, 'Lounge Table Light') and then you can associate it to a specific room (by dragging the light into the room). Now place your smart light in the room you created in Step 3. And that is it, the smart light is successfully added.

Note that there is no need to configure any other item (such as a light switch to control the smart light we've just added) since the minimum requirement for testing our PicoMite controller is just a single smart light.

From the Home page, you will now see the room that you just created. To the right, you will see a 'slide switch' which when tapped, will toggle the smart light between being turned on and turned off. Check that this does work.

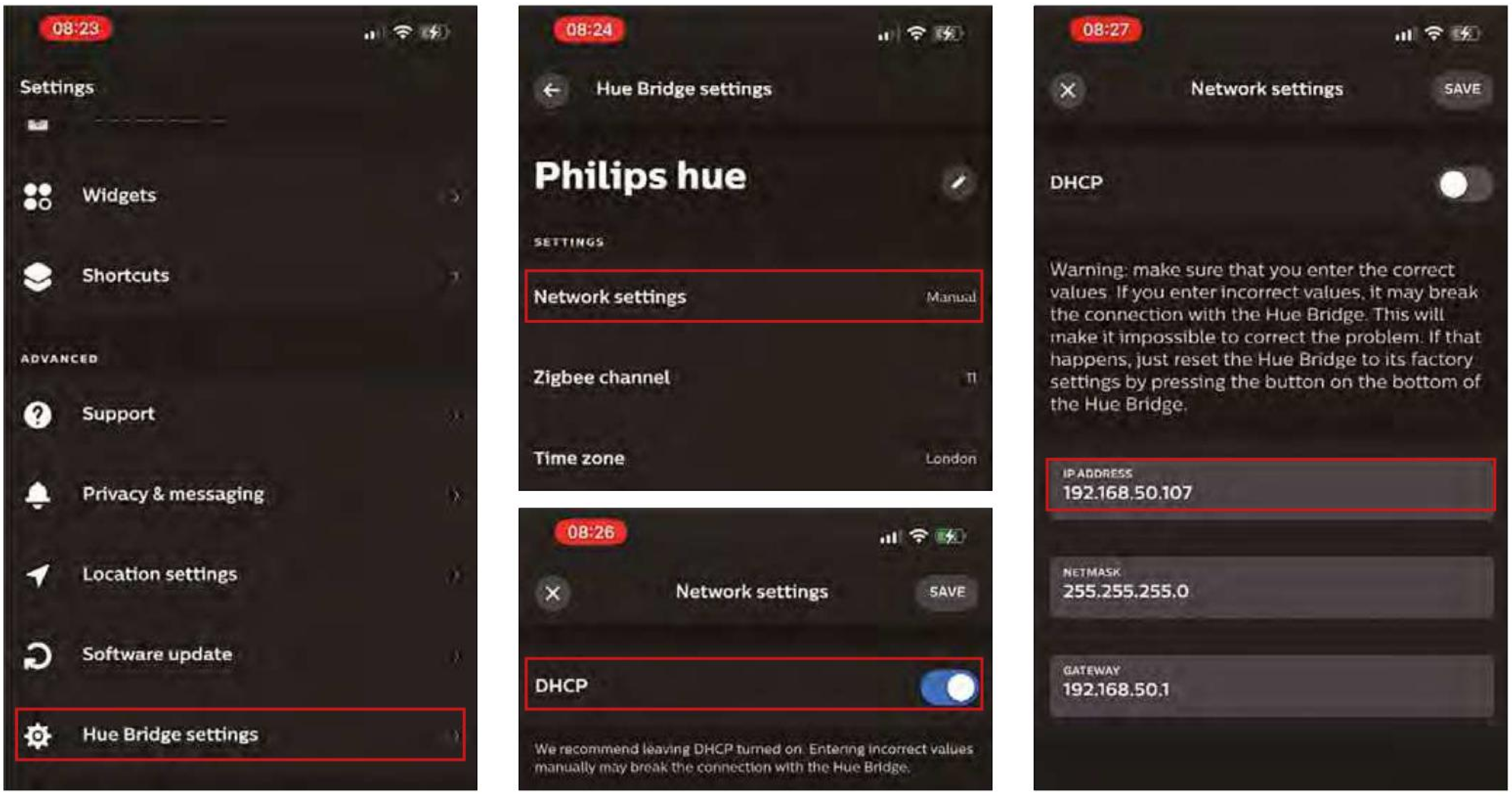
The above four steps are just standard Hue setup procedures. By using the App to add new rooms and new lights, you can expand on the number of smart lights in your home.

5. Identify the Hub's IP address

The Hue Hub is connected to your local network, and to communicate with it we will need to know its IP address. This is easy to find from within the Hue App; however, we ideally want to make it 'static' too so that it doesn't change. That way, our PicoMite controller will always communicate to a single known IP address that remains the same.

First, let's find the current IP address by using the 'Settings' page in the App (bottom right-hand option), and selecting 'My Hue System' near the top of the list (Fig.7a). You will then see a 'Philips hue' option with an 'i' icon on the right-hand side (Fig.7b). On tapping the 'i', it will display information relating to the Hue Hub, including the IP address (Fig.7c). Make a note of this IP address and keep it at hand – we will need it for the following steps.

Next, make this a static IP address. From the Settings page, scroll down to 'Hue Bridge settings' (Fig.8a). Select 'Network settings' (Fig.8b), then tap the DHCP switch (Fig.8c) so that it is off. Here you can set the IP address obtained above (it will likely



Network settings: Manual

Zigbee channel: 11

Time zone: London

DHCP

We recommend leaving DHCP turned on. Entering incorrect values manually may break the connection with the Hue Bridge.

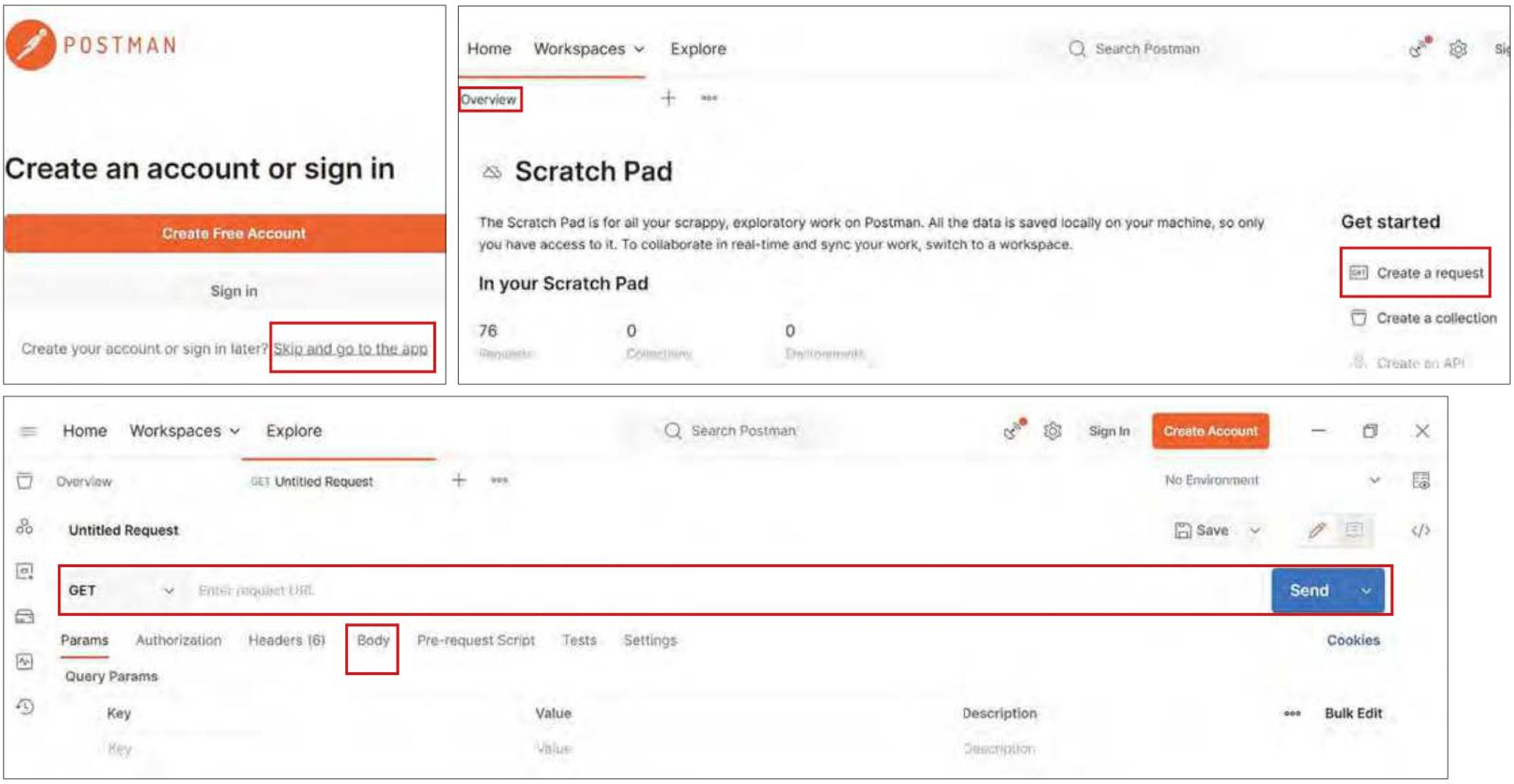
Warning: make sure that you enter the correct values. If you enter incorrect values, it may break the connection with the Hue Bridge. This will make it impossible to correct the problem. If that happens, just reset the Hue Bridge to its factory settings by pressing the button on the bottom of the Hue Bridge.

IP ADDRESS: 192.168.50.107

NETMASK: 255.255.255.0

GATEWAY: 192.168.50.1

Fig.8. a) (left) To make the IP address static, select 'Hue Bridge settings' from the 'Settings' page; b) (middle top) then select 'Network settings'; c) (middle bottom) DHCP will be on; d) (right) and tapping it will turn it off where the IP address will be displayed.



POSTMAN
Create an account or sign in
Create Free Account
Sign in
Create your account or sign in later? Skip and go to the app
Home
Workspaces
Explore
Search Postman
Overview
Scratch Pad
Get started
Create a request
Create a collection
Create an API
In your Scratch Pad
76
0
0
Requests
Collections
Environments
Sign In
Create Account
GET Untitled Request
No Environment
Untitled Request
Save
GET
Enter request URL
Send
Params
Authorization
Headers (6)
Body
Pre-request Script
Tests
Settings
Cookies
Query Params
Key
Value
Description
Bulk Edit

The Scratch Pad is for all your scrappy, exploratory work on Postman. All the data is saved locally on your machine, so only you have access to it. To collaborate in real-time and sync your work, switch to a workspace.

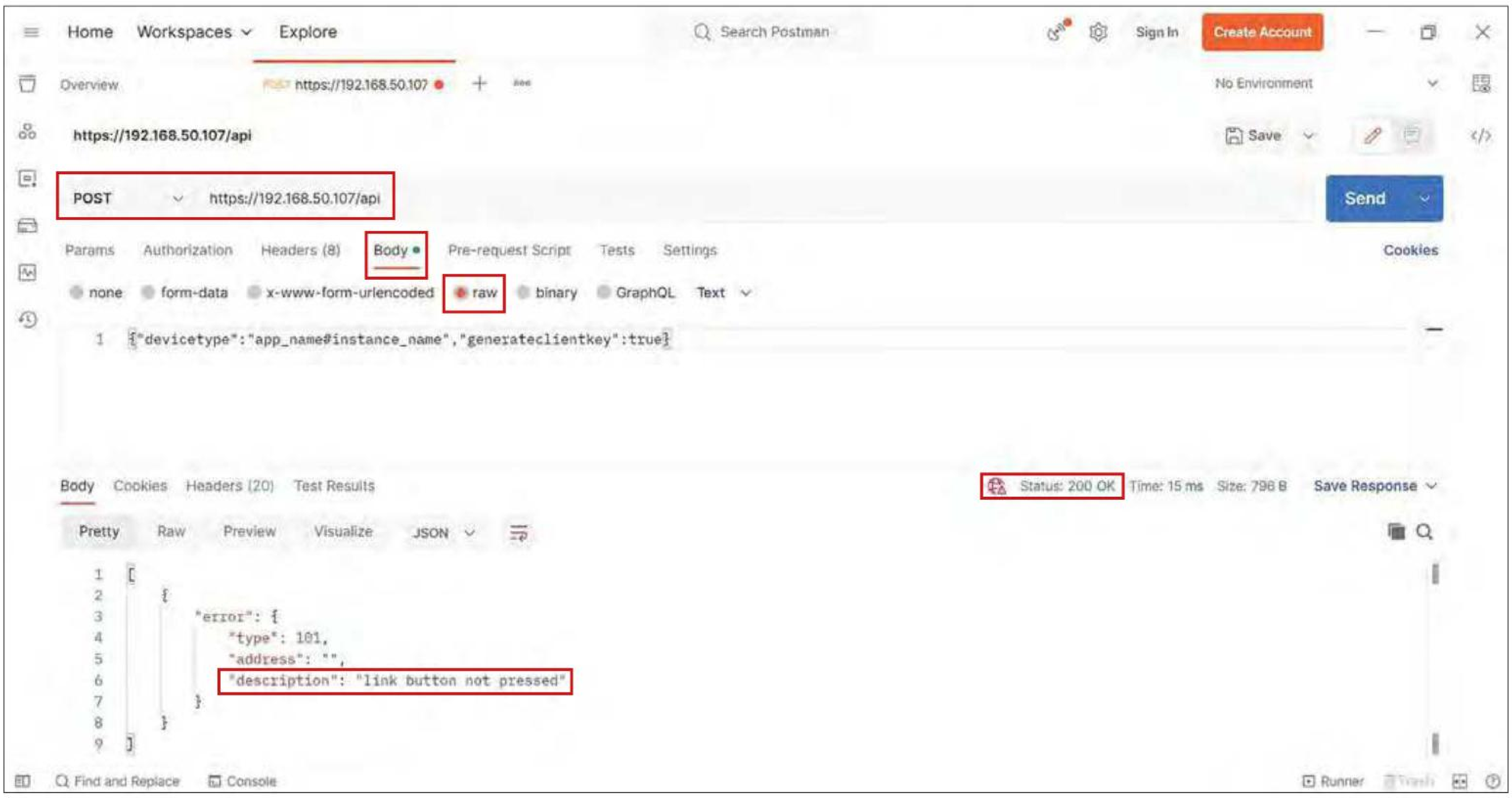
Fig.9. a) (top left) After installing Postman, you will see a screen inviting you to create an account, b) (top right) Select 'Skip to go to the app' to see the 'Overview' tab; c) (bottom) Select 'Create a request' and then you will be able to enter in an API request.

be set already) – see Fig.8d. The point is to make sure DHCP is switched off so that the Hub's IP address doesn't change.

6. Obtain a unique API key

Without an API key, we will not be able to communicate with the Hue API to control any smart lights. A unique API key is issued by the Hue Hub, and it is only issued when a request is sent to the Hub (a request only needs to be performed once). To be able to send the request to the Hub, we will need to send a basic command to the Hub (that doesn't require an API key) using a piece of computer software that is able to send APIs. If this is starting to sound complicated – don't panic. We will simply be downloading a program called 'Postman' which will allow us to send a message from our computer to the Hue Hub, and get a response back from the Hub. For example, we can send a request for an API key, and get a response back containing the unique API key number. For anyone experienced with APIs, you may already have an API tester that you can use instead of Postman.

To download Postman, visit **postman.com/downloads** and follow the instructions. Once installed, run it and you will see a screen that resembles something like that shown in Fig.9a. Click 'Skip….' to see the 'Overview' tab



Home
Workspaces
Explore
Search Postman
Sign In
Create Account
Overview
POST https://192.168.50.107
No Environment
Save
Send
Params
Authorization
Headers (8)
Body
Pre-request Script
Tests
Settings
Cookies
none
form-data
x-www-form-urlencoded
binary
GraphQL
Text
Body
Cookies
Headers (20)
Test Results
Save Response
Pretty
Raw
Preview
Visualize
JSON
Find and Replace
Console
Runner
Trash

https://192.168.50.107/api

POST https://192.168.50.107/api

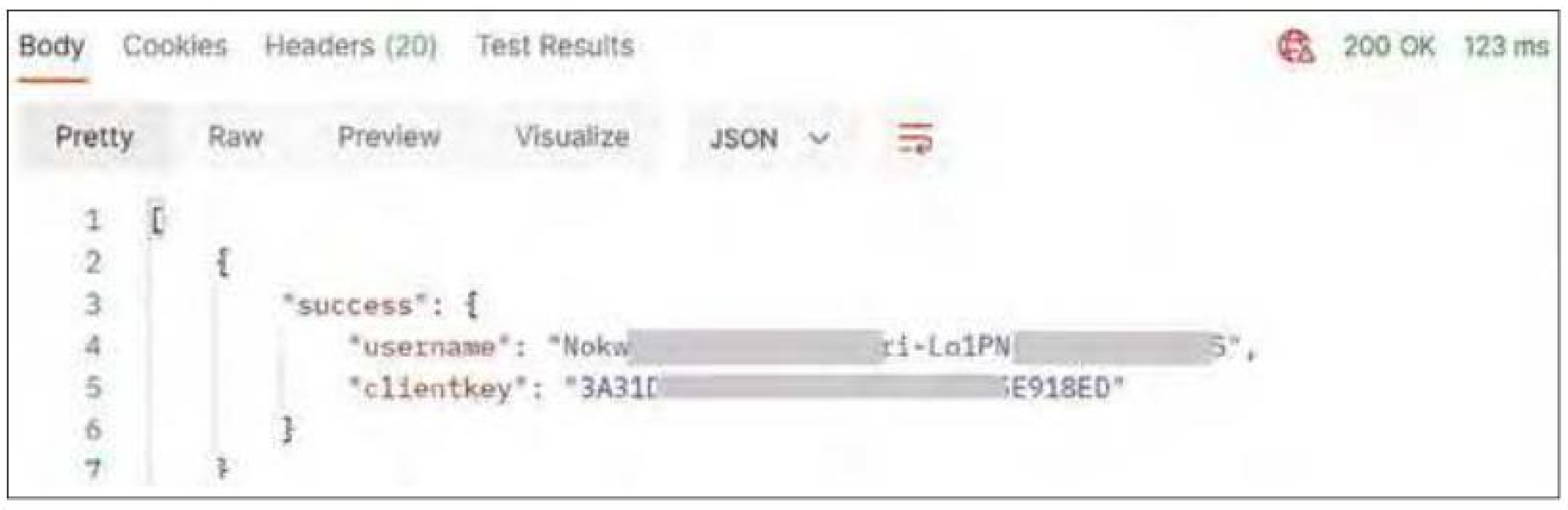
● raw

```
{"devicetype":"app_name#instance_name","generateclientkey":true}
```

Status: 200 OK Time: 15 ms Size: 798 B

```
[
    {
        "error": {
            "type": 101,
            "address": "",
            "description": "link button not pressed"
        }
    }
]
```

Fig.10. When sending the request to get an API key, the Postman screen should look something like this. The response from the Hub is indicating that the Hub's round button needs to be pressed. Note the Status showing 'Status: 200 OK'. Any other value means something is wrong!


Body
Cookies
Headers (20)
Test Results
200 OK
123 ms
Pretty
Raw
Preview
Visualize
JSON

```
[
    {
        "success": {
            "username": "Nokw[redacted]ri-Lo1PN[redacted]5",
            "clientkey": "3A31D[redacted]E918ED"
        }
    }
]
```

Fig.11. Once the Hub's link button is pressed, if we send the same request again, this time it will respond with the required API key (for security reasons, it is shown here partially greyed out!). Note that the required API key number is in the 'username', and NOT in the 'clientkey'.

(Fig9b) and then select 'Create a request'. This will take you to the screen where you enter the API request (Fig.9c).

To send the request for an API key, change 'GET' to 'POST', and in the 'Enter Request URL' input box, type the following (but using the IP address of you Hub obtained in step 5):

`https://``192.168.50.107`**`/api`**

Next, select the 'Body' tab (under the 'Request URL' just entered), and below that, select 'RAW'. This will allow the request to be entered in the box. The request we want to send is:

```
{"devicetype":"app_name#instance_name",
"generateclientkey":true}
```

Once this is entered, press the blue 'Send' button near the top-right of the screen. If everything is entered correctly, the request will be sent to the Hub at the IP address entered, and the Hub will send a response that can be seen towards the bottom of the screen. Refer to Fig.10 as to how the screen should look for this step. Looking at the response, you will see that it contains the words:

```
"description": "link button not pressed"
```

Press the round button on top of the Hub, and then resend the same request again.

This time it will respond with two bits of information, as shown in Fig.11. Rather bizarrely, the API key that we need is the value returned for the 'username' (and not the 'clientkey') so be very careful to make a note of the 'username' for our API key. With this noted, we are ready for the next step.

7. Get a list of smart light IDs

We will now use Postman again to send another request. We can simply edit the request we just used to get the API but ensure your make the following changes.

The Request URL needs to be set to the following (but using *your* Hub's IP address):

`https://``192.168.50.107`**`/clip/v2/resource/light`**

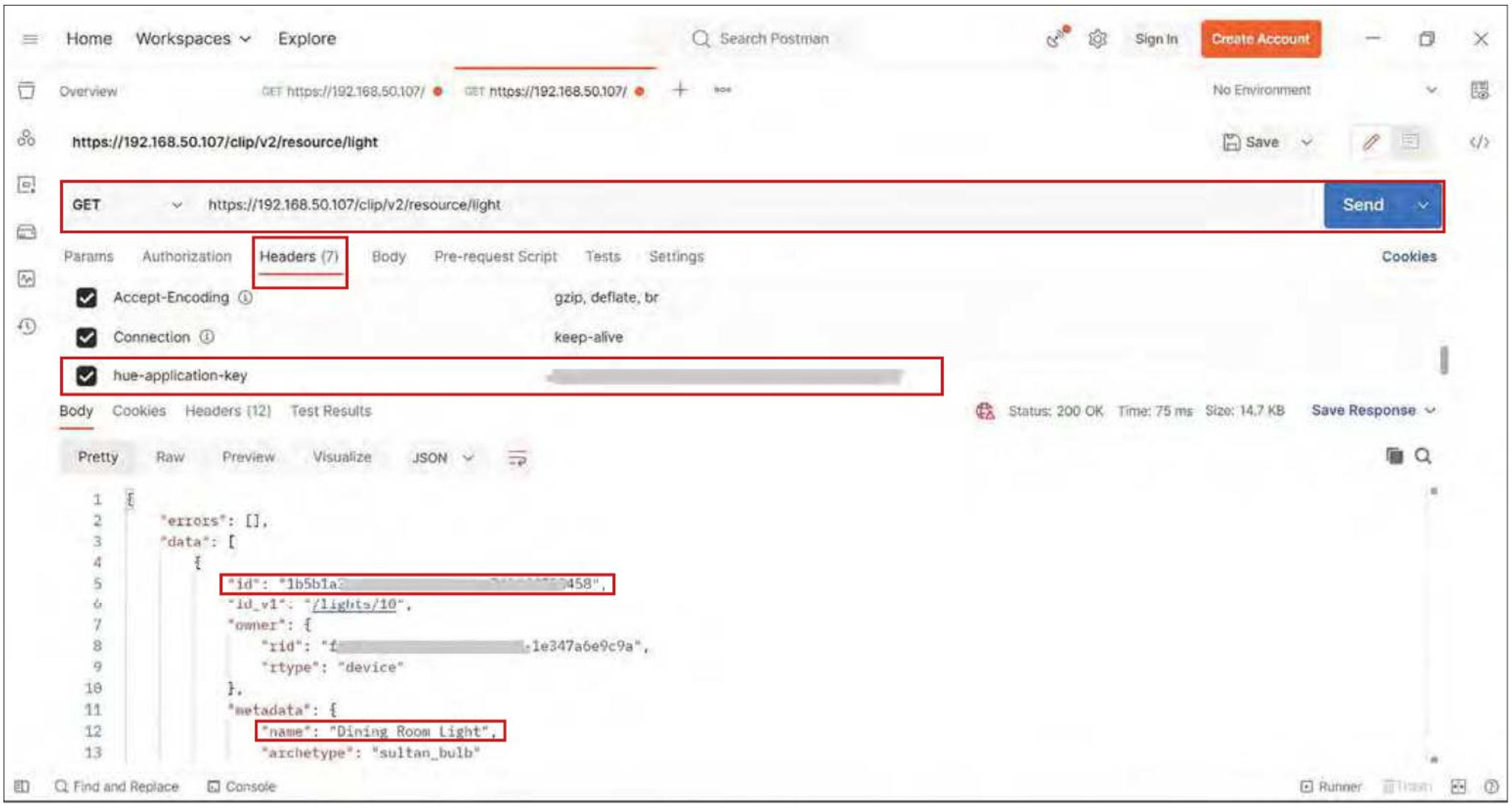
Next, change 'POST' back to 'GET', and then select the 'Headers' tab underneath (rather than the 'Body' tab). Here we need to enter our API key as follows. In the 'Key' input box, type `hue-application-key` and in the 'Value' input box, type in your API key generated from Step 6. You then press the 'Send' button to send the request. Your screen should then look similar to that shown in Fig.12, but with a response that lists data from your setup.

The bit of data we're interested in is the first `"id"` value under the `"data"` heading (as highlighted in Fig.12). This is the smart light ID we that we will require for testing our PicoMite controller, so make a careful note of it.

If you are lucky enough to have more than one smart light, then scroll through the response until you reach the required light you wish to control. If you noticed from Fig.12, the second line from the bottom of the screen-shot response shows the `"name"` as `"Dining Room Light"` so you can use this as a reference to the different lights.

Test to control a single smart light

With all the above steps completed, it is now time to see if we can control a smart light with our PicoMite controller test circuit. Download the file **SLC_Test2.txt** and load it into your PicoMite. Before running the code, you will need to edit the first three lines of uncommented code so that it knows the following three things:


Home
Workspaces
Explore
Search Postman
Sign In
Create Account
Overview
GET https://192.168.50.107/
GET https://192.168.50.107/
No Environment
Save
Send
Params
Authorization
Headers (7)
Body
Pre-request Script
Tests
Settings
Cookies
Body
Cookies
Headers (12)
Test Results
Save Response
Pretty
Raw
Preview
Visualize
JSON
Find and Replace
Console
Runner
Trash

https://192.168.50.107/clip/v2/resource/light

GET https://192.168.50.107/clip/v2/resource/light

☑ Accept-Encoding: gzip, deflate, br
☑ Connection: keep-alive
☑ hue-application-key: [redacted]

Status: 200 OK Time: 75 ms Size: 14.7 KB

```
{
    "errors": [],
    "data": [
        {
            "id": "1b5b1a[redacted]458",
            "id_v1": "/lights/10",
            "owner": {
                "rid": "f[redacted]1e347a6e9c9a",
                "rtype": "device"
            },
            "metadata": {
                "name": "Dining Room Light",
                "archetype": "sultan_bulb"
```

Fig.12. Here we can see how the request (and response) appear in Postman when obtaining a list of smart light IDs.

- Your Hub's IP address (Step 5)
- Your unique API key (Step 6)
- The Light ID (step 7) for the single smart light which we want to control.

Note that when you used the initial Test1 program (to check the test circuit), you edited the first two lines to define your Wi-Fi network name (SSID) and Wi-Fi password. A specific `AT` command that was used in that program (`AT+CWJAP`) stores this network information in the ESP32's internal Flash memory. Hence, we don't need to define it again in this second test program. So, an important point to stress here is that you must ensure that you have `RUN` the **SmartLightController_Test1** program (on the same Wi-Fi network) prior to using the **SLC_Test2** program code. For those who are inquisitive, whenever you power up the ESP32 having successfully complete Test 1, the ESP32 will automatically attempt to connect to the Wi-Fi network name which is stored in its Flash memory. This only takes a couple of seconds after powering up the ESP32 module, and if it does successfully connect, the ESP will respond on its Tx serial output with the message:

```
WIFI CONNECTED
WIFI GOT IP
```

Back to **SLC_Test2**, go ahead and `EDIT` the program code to enter your Hub's IP address, your API key and the required Light ID you wish to control. On running the program, nothing will appear to be happening, but you will observe a simple graphic on the touchscreen display. If you now tap the right-hand side of the touchscreen, your smart light should turn on; and tapping the left-hand side of the touchscreen should turn it off. If this is what you observe, then congratulations, you have everything configured correctly.

If Test2 does not control the smart light, then carefully check that the three lines at the start of the program code have the data entered 100% correctly. Any single character missed (or that is incorrect) will result in it not working.

The code has been used on several different Hue setups at different locations (and hence on different Wi-Fi networks too), and the only time it failed was when I incorrectly entered a light ID into the program code. As always, reach out by email if you find you are struggling; but do ensure that you have methodically followed all the steps in the sequence presented in this article, without missing any of them out.

Once again, understanding how the program code works is not important at this stage. Test2 is all about ensuring we have the correct API key, and that you understand how to extract a smart light ID. However, do feel free to have a play and see if you can modify the code and control a second smart light.

Next time

Now that we have everything in place to be able to successfully communicate with the Hue Hub, we are ready to work on the program code. In *Part 3* of our *Smart-light Controller* project we will discuss how to implement the features we wish to add, such as selecting a specific light from a list of available lights, and how to control it – turning it on/off, or adjusting brightness.

Until then, stay safe, and have FUN!

Questions? Please email Phil at:
contactus@micromite.org

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AUDIO OUT

By Jake Rothman

Potentiometer scratching – Part 1

Ever since electronic audio started over a century ago, there have always been volume controls based on variable resistors – potentiometers. And, right from the start those pots suffered from an annoying fault – when operated they cause the audio output to go 'scratch, crackle and bang'. Pot scratching is the most common analogue audio fault. Often, this is down to potentiometers just wearing out, but it's also the result of poor circuit design and parts choice. I've always believed the rotary potentiometer or 'pot' is one of the most effective human controls invented. It would be a shame if the physical knob became just another software icon in a skeuomorphic world. This month and next I'll discuss how to overcome its main weakness, rotational noise.

Potted histories

As a child in the 1970s, I was able to earn steady pocket money fixing scratchy volume controls in many radios and other consumer audio products. Some still scratched even when replaced due to leaky capacitors and bad design, but I didn't know what was going on at the time. There's not much material on the subject. The earliest article I've found was by E Dexter in *Practical Wireless* from August and September 1962. It was mainly concerned with valve circuits. James Kerrick did an article called *Clearing Noisy Volume Controls* in the April 1974 issue of *Radio and Electronics Constructor* magazine. Another one was by CH Banthorpe in *Circuit Ideas*, *Wireless World* (April 1971).

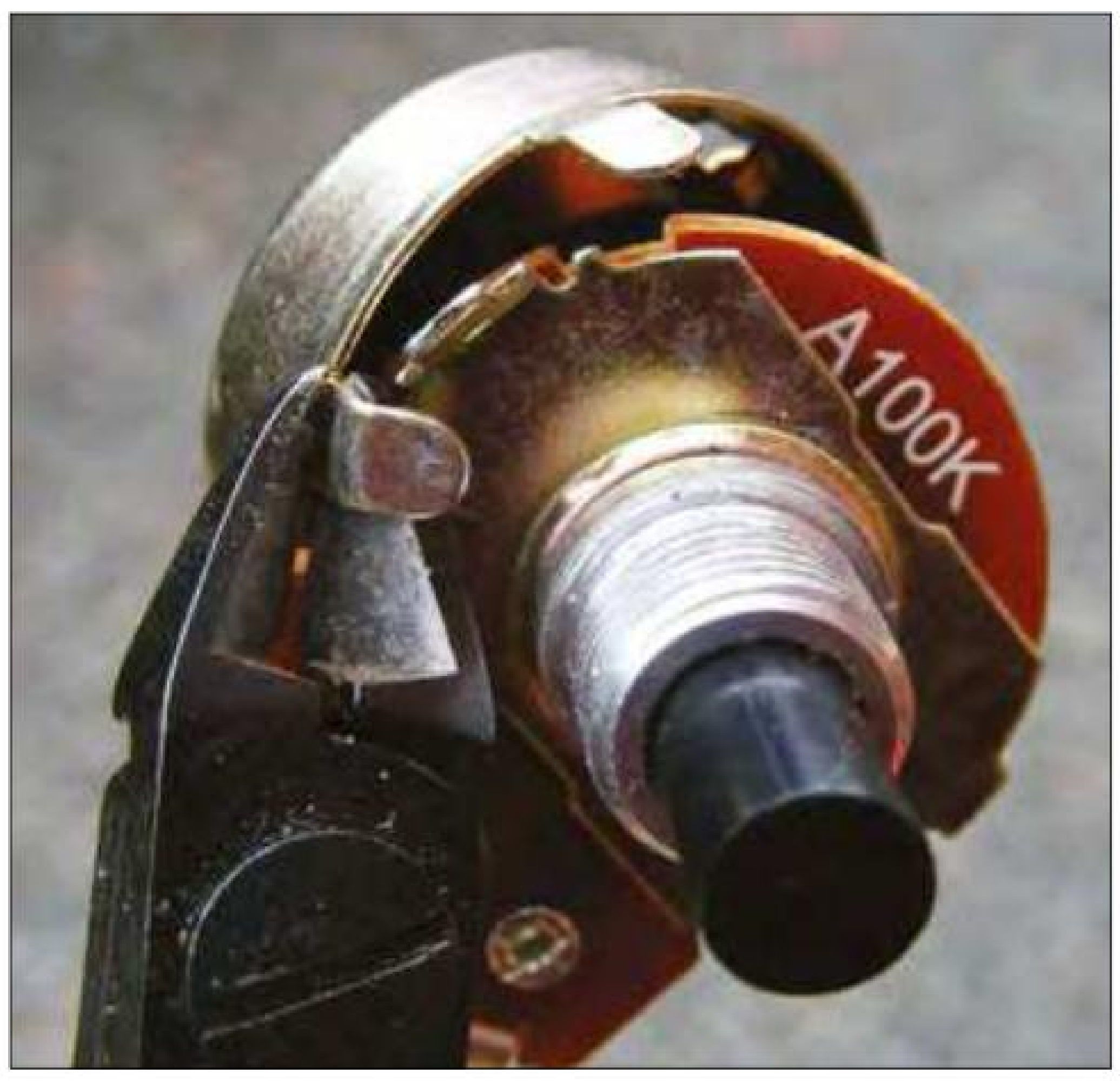

Fig.1. The best way to understand the component parts of a pot is to open one up. Most are simply clamped together. Just open up the tabs with side cutters.

I've been researching pots for 35 years and since rotational noise is rarely mentioned in device datasheets, real-world practical experience is important when it comes to parts choice and circuit design – and that is exactly what I will write about here.

Basic construction

The construction of potentiometers has been covered before by *PE* (November 2015), but it's as well to be familiar with the basic assembly. The best way to show this is to pull a device apart. The Alpha 24mm pots supplied by Rapid are the easiest to disassemble – and they can easily be put back together again. The technique of opening up the metal tabs is shown in Fig.1. The track, wiper and the centre contact slip ring assembly are all visible.

Can't stand the noise

The whole point of a potentiometer is to provide an infinitely smooth change in resistance with rotation. That is the theoretical ideal, but in practice there are always irregularities in the track resistance. These modulate any voltage that is across the pot and cause noise as it is rotated.

Pot technology

Manufacturers have developed quite a few ways to create potentiometers. The following is an overview of the most-important varieties. Note that in the following descriptions the 'track' is the resistive material between the pot's two end terminals, and the 'wiper' is the part that moves along the track and which is connected to the pot's third terminal.

Wirewound potentiometers

Wirewound pots (Fig.2.) give the best stability and accuracy, along with potentially massive power dissipation capabilities. They were historically the first pots. However, nowadays, their only audio use is mid-range and treble level controls in loudspeaker passive crossovers, where very low values of resistance (2Ω to 100Ω) and high power ratings (2W to 5W) are needed. Wirewound pots have stepped resistance changes which give a perceptible 'whooshing' noise as the pot is rotated, sometimes called zipper noise.

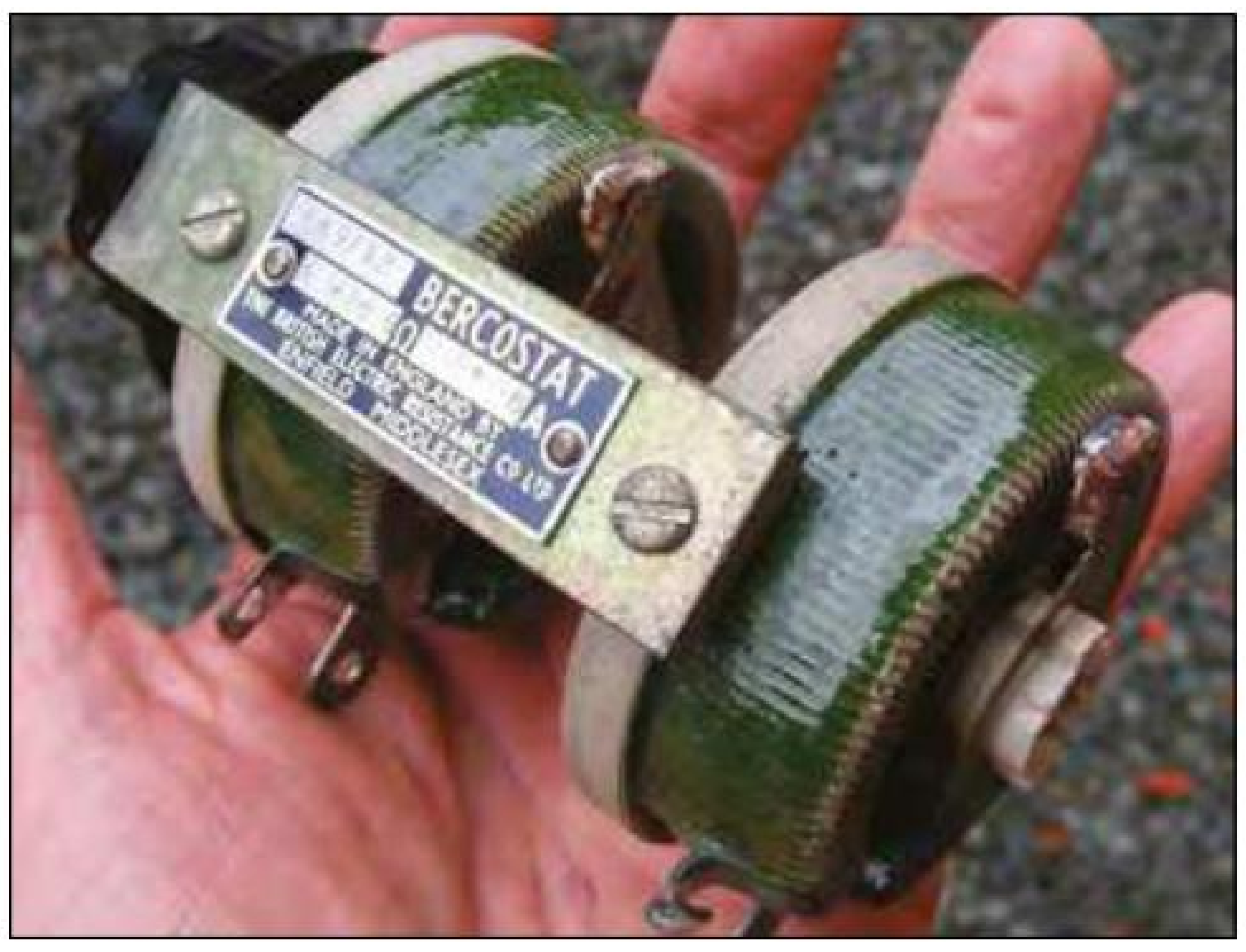

Fig.2. The earliest pots were wirewound. This is an unusual dual-gang high power tweeter level control.

Carbon potentiometers

Early radio designers later moved on from wirewound pots to using carbon for the resistive track, employing a similar material to carbon film resistors. Those made by Morganite (Fig.3), who specialised in carbon brushes and railway pantograph pickups were the favourite, and were adopted by nascent Hi-Fi industry pioneers such as Quad in their 1950s valve pre-amps.

The tracks of carbon pots normally consist of fine carbon-black mixed with a phenolic resin and some kind of insulating filler, such as clay. They still have irregularities, but they are of a smooth random nature, as shown in Fig.4. Typically, they have rapid transitions of around ±0.2 to 3% of the resistance of the average track value as the wiper is moved. If this parameter is specified it is called dynamic noise. It is always given as an initial value for a new pot. As the track wears the surface gets rougher and the noise increases.

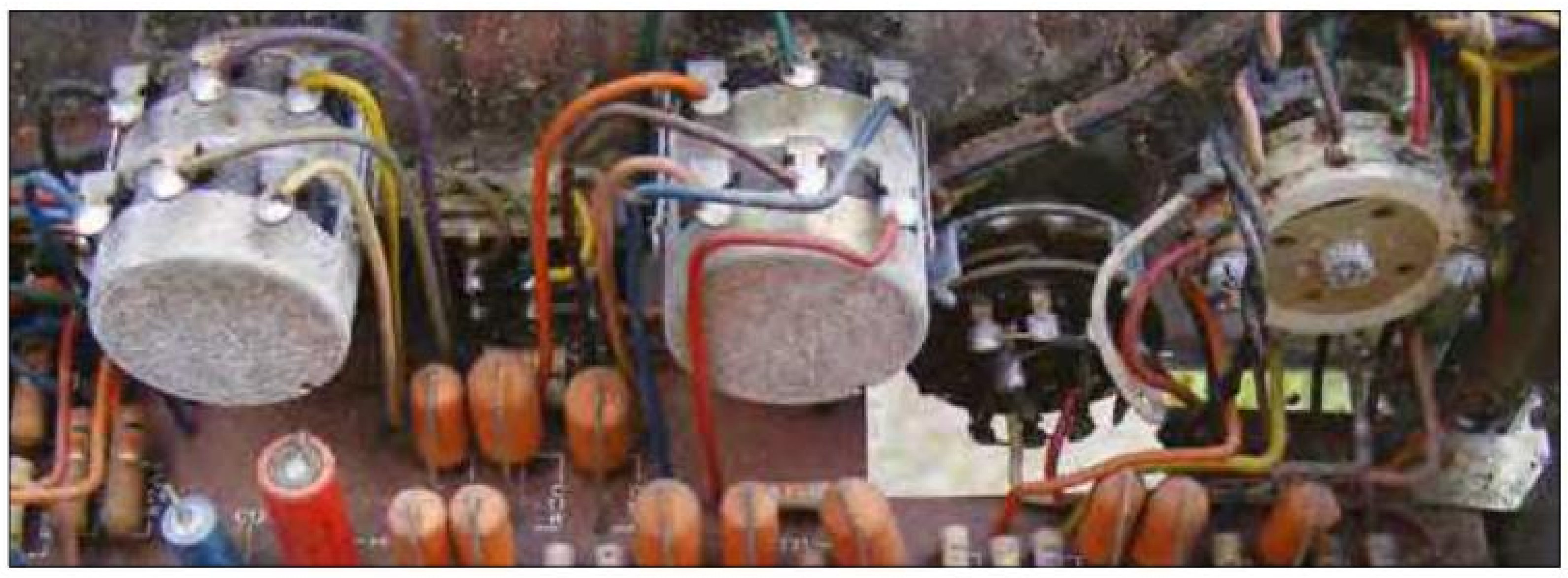

Fig.3. Very early Hi-Fi used these Morganite carbon-track pots. This 1964 germanium Leak Stereo 30 had them. They still work despite oxidation and dirt.

Track coating recipes are generally closely guarded trade secrets, although Omeg told me their tracks used carbon black, phenol-aralkyl thermosetting resin, a toughing agent such as Butar resin and a dry lubricant, such as PTFE and solvents. They call it 'conductive polymer'. The cheapest way to make a pot track is to just spray or screen print a carbon-ink film onto a circle of Paxolin or phenolic-resin-bonded paper. The best carbon-track pots are the Alps and Alpha (Fig.5) pots that adorn most consumer amplifiers. Carbon tracks have the shortest lifetimes typically 10,000 to 20,000 rotations. Morganite found the average radio volume control in the 1950s was moved about 2000 times a year. In busy professional audio studios, the main volume control or monitor pot may only last a year or two.

Moulded track potentiometers

A longer-lasting technology is a thicker track of hot-moulded carbon, typified by the old Plessey E series (Fig.6) which were used in Neve modules and 1960s Bush radios, such as the famous TR82 (shown in Fig.6). These radios are still made as Chinese re-issues today. Resistance tolerance is the worst of all pot types with moulded track, similar to carbon composition resistors. However, in potential divider applications, such as volume controls driven by low impedance and loaded by a high impedance, variations in the track resistance value have very little effect.

Conductive plastic/polymer potentiometers

For lowest noise, use conductive plastic tracks made from extra-fine carbon bonded together with epoxy resin and given a highly polished surface. This was first popularised in the famous Penny and Giles faders used in expensive mixing desks derived from aeronautical position sensors. These pricey technologies still suffer from irregularities due to the finite size and clumping of the carbon particles. Minimising the effect of this is where the circuit design comes in. One day we may get truly smooth carbon pots using nanoparticles.

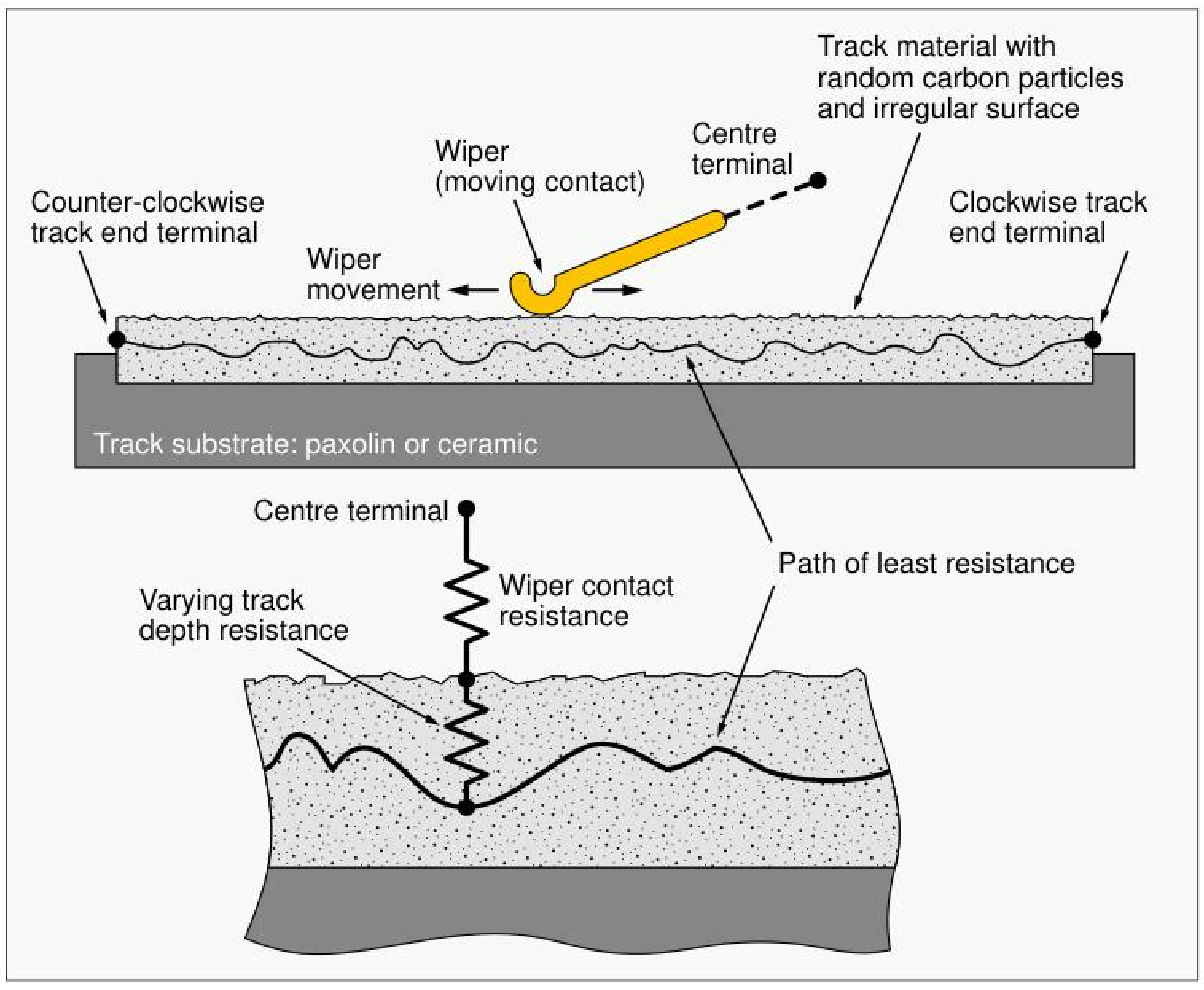
Track material with random carbon particles and irregular surface
Centre terminal
Wiper (moving contact)
Counter-clockwise track end terminal
Clockwise track end terminal
Wiper movement
Track substrate: paxolin or ceramic
Centre terminal
Path of least resistance
Wiper contact resistance
Varying track depth resistance

Fig.4. Diagram showing how random resistance variations/ irregularities occur with rotation.

Cermet potentiometers

Another common track material is cermet, a ceramic and metal glaze fired onto a ceramic insulating base. This is used in instrumentation applications where high stability and high dissipation are regarded as more important than rotational noise. They a have a shorter rotational life, not because the track wears out, but because the wiper grinds away on the hard track. Cermet is the best trimmer technology to use for adjusting quiescent current and offsets. Cermet pots do not make good volume controls because the granular tracks are scratchy and only come in linear taper. They are great for setting values – trimming – and then simply left at that value.

Wipers

Most wipers are made from a springy metal, such as brass. For lower rotational noise, multi-fingered wipers are employed to average out track irregularities. If you want a quiet pot, four fingers is a sensible number. Silver plating also helps. The Bourns pots have a unique wiper with at least 10 fingers which accounts for their superiority.

Moulded track pots use a single carbon brush wiper which reduces wear and has a large contact area. Most importantly, they do not oxidise, although the slip ring they run on may do so. An important audio aspect of carbon brush wipers is that they have a small but significant resistance of around 20Ω called the 'end-stop resistance'. Its presence means the volume control may not go fully off. A cheap way of getting extra wipers and lower noise is to put both gangs of a dual Alpha pot in parallel. Using this technique, the rotational noise is reduced by 3dB.

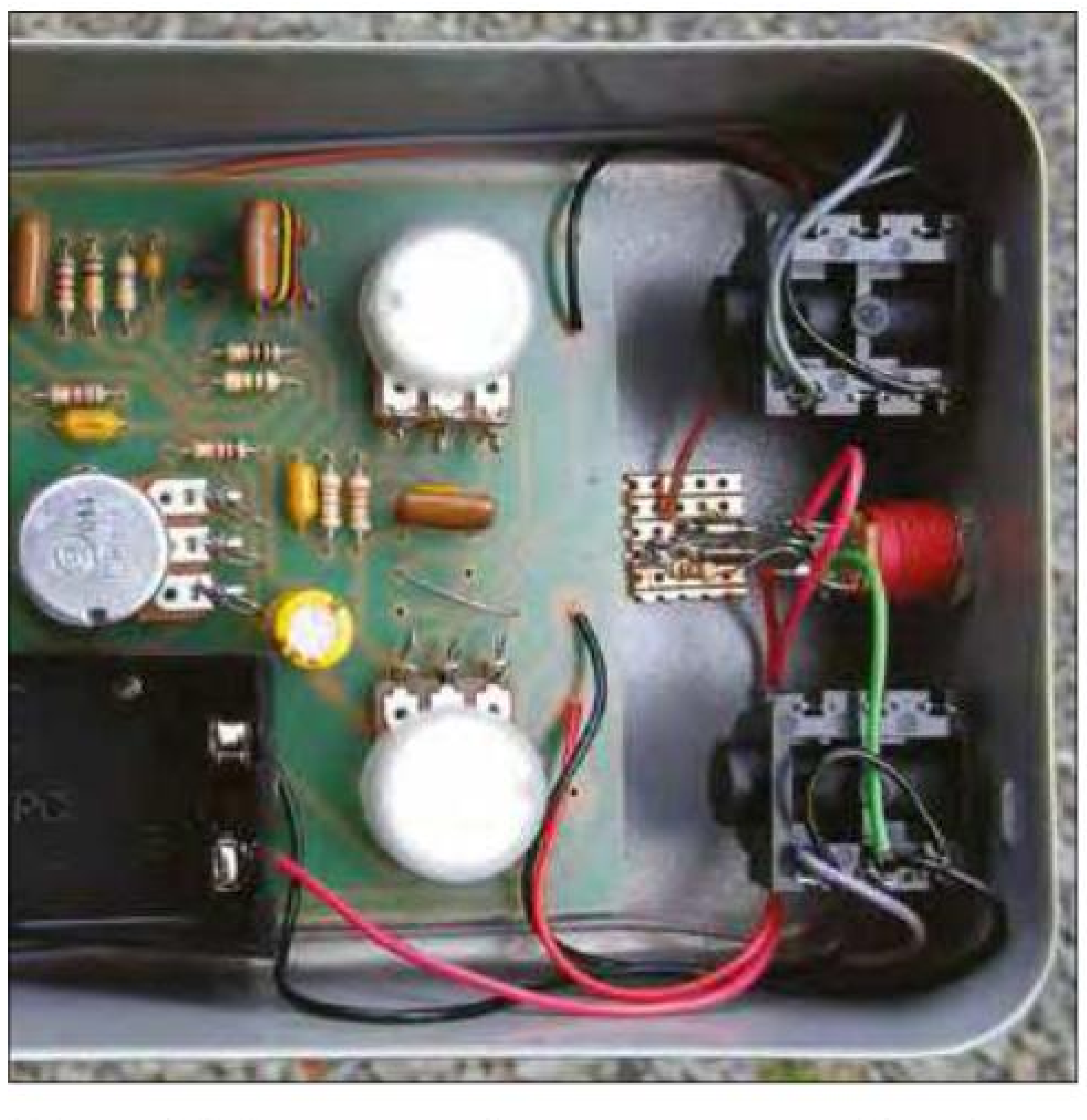

Fig.5. Alpha pots give very cost effective performance. Here the 16mm versions are being used in a Colorsound Silver Tonebender guitar pedal.

Fig.6. The stylish Bush TR82 radio used Plessey E series pots. They rarely fail apart from needing cleaning and their leaky electrolytic capacitors changing.

Pot taper

Volume controls have always traditionally had 'logarithmic' rather than linear tracks to compensate for the logarithmic nature of human hearing. I've put logarithmic in inverted commas because the pot track resistance actually rises exponentially as the pot is rotated in a clockwise direction. This gives a corresponding exponential rise in signal voltage, which results in a smooth subjective control of volume as the pot is turned. The Austrian company Ruwido mark their 'log' pots as '+exp'. The most common log signifier is 'A' after the value.

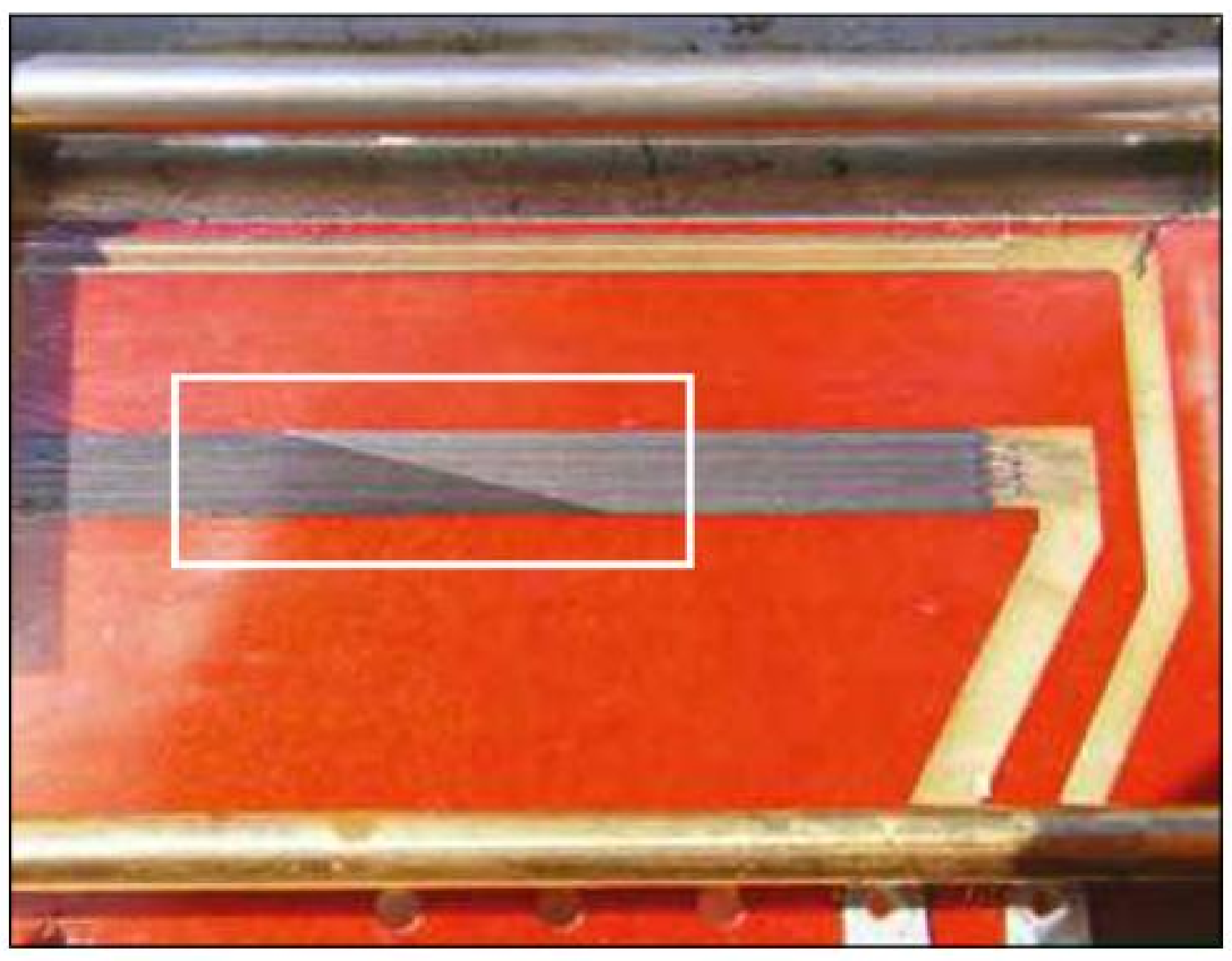

Fig.7. Transition area of an Alps log fader.

Linear pots are marked ‘B’ and anti-log devices with ‘C’. Just to confound audio engineers, there are loads of contradictory proprietary marking systems. European manufacturers and the British company Omeg swap the A and the B, while Bourns uses D and Allen-Bradly uses R in their long part numbers for log pots. Preh and other German companies mark them +log. Always check a datasheet or test a device with a DMM set to Ω (ohms).

Many log pots make the required curve by overlapping segments of different resistance material. This is effectively a combination of straight lines of different slopes, sometimes called a piece-wise linear approach. The noise tends to get worse over the main transition area (Fig.7) because the irregularities are greater. This occurs in a band around at 70% of the rotation in most log pots.

Pot position

It has to be accepted that pots are inherently noisy devices, they are, after all, a moving contact. So it is sensible to place them in the higher signal level parts of the audio system. A pot placed just after a microphone followed by +60dB of gain would make almost as much noise as the microphone. Similarly, many early radios were compromised in this respect because the audio level was only around 20-100mV followed by lots of gain. A pot placed after a preamplifier to bring the signal up to around $1V_{rms}$ just before the power amp is fine.

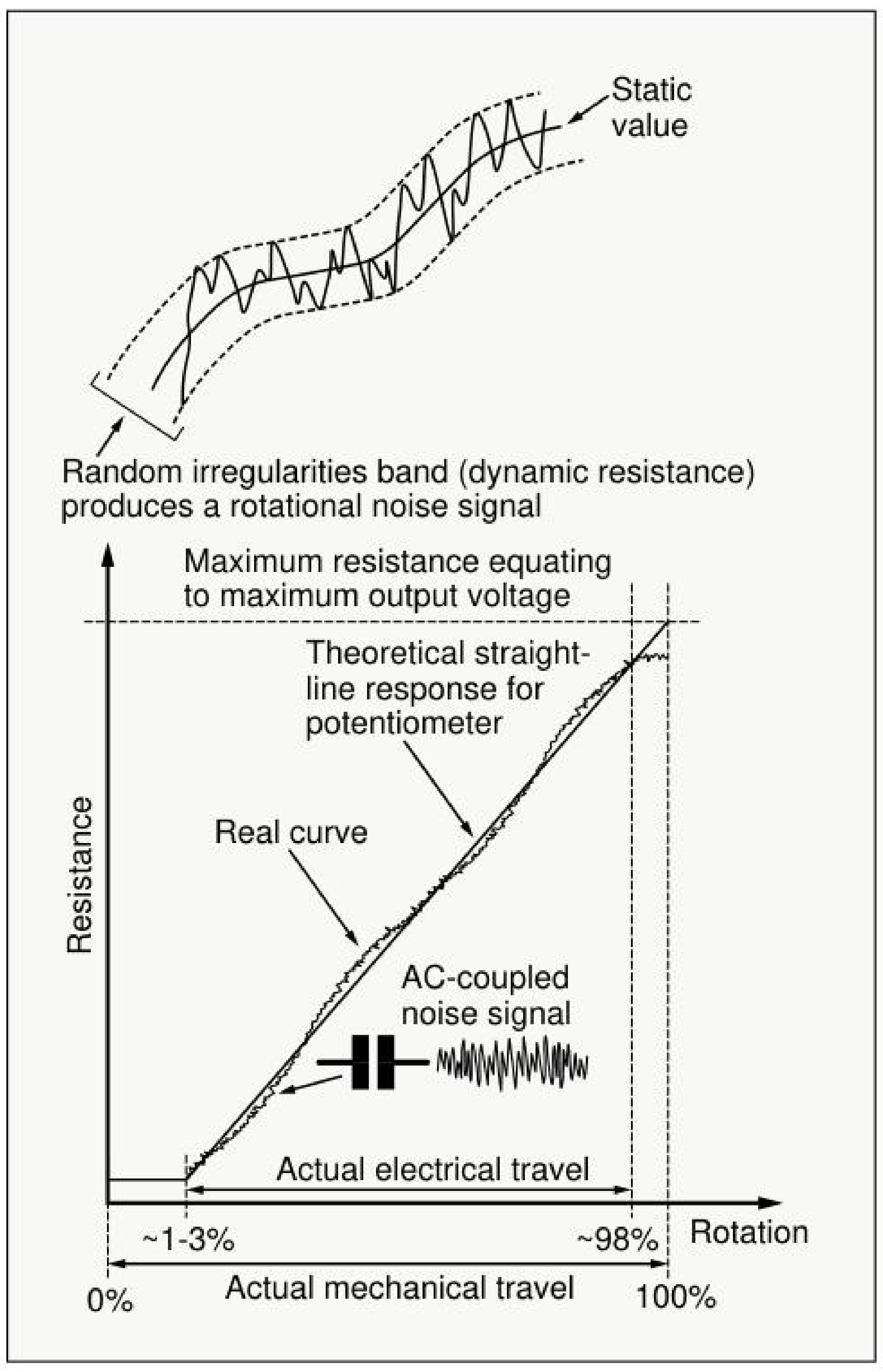

Fig.8. DC on an irregular potentiometer track translates into a noise signal.

Pot value

It is well known that fixed resistors develop Johnson noise that is proportional to their resistance. However, higher resistance value pots suffer additional rotational noise due to the lower proportion of carbon in the track material, making it rougher. The higher impedance generates more noise voltage for a given leakage current and pickup of extraneous noise is also emphasised. It’s best to keep volume controls in the region of 1kΩ to 22kΩ. Some old valve circuits will use values up to 2.2MΩ, but noise is expected with these systems. Modern audio op amps will drive a load of 600Ω without suffering gross distortion and many designers are now using low-value pots to minimise noise.

Dump the DC

It’s essential when controlling audio with pots that there is no superimposed DC voltage across the track or wiper. Always check for DC voltage on the wiper with a high impedance (>10MΩ) multimeter. The pot’s track irregularities do an excellent job of converting DC to a random noise signal as the wiper moves. The AC component is passed on by the capacitor coupling the wiper – see Fig.8. The noise gets louder, the faster the pot wiper is rotated.

The volume pot must be isolated with capacitors on its input and output as shown in Fig.9. If the capacitors are electrically leaky, then noise will develop. A scratchy pot is often the sign of a leaky coupling capacitor, typically an electrolytic one. It is possible to use pots without capacitors where the driving stage DC offsets are nulled-out and the wipers are loaded by FET inputs, but in my experience such systems often drift, developing leakage currents and noise over time.

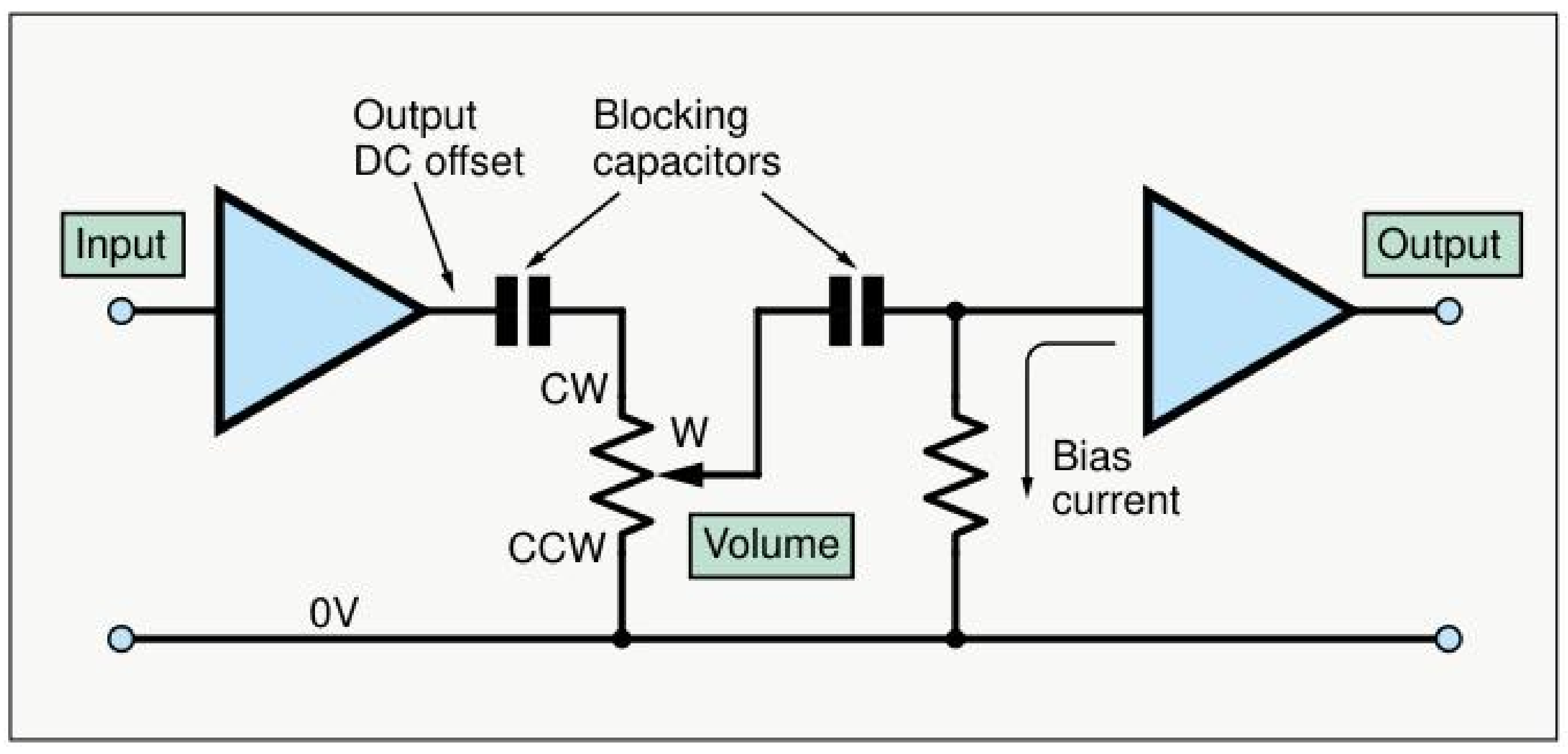

Fig.9. Block DC from a pot using capacitors.

The basic idea of the pot scratching articles of the 1970s mentioned earlier was to increase the amplifier input impedance loading so that a plastic-film coupling capacitor can be used instead of a leaky electrolytic capacitor with a pot’s wiper. Typically, this involved placing a buffer amplifier after the wiper, as shown in Fig.10.

The main signature of DC leakage is that the crackling occurs when there is no signal when the pot is moved. If it only occurs with a signal present, that is a sign that the problem is track wear or wiper contact problems. The most revealing signal for this is a low distortion sinewave of around 300Hz. This is a useful check for mixer faders. Using music usually hides the minor crackles.

Next month, we will dive deeper ito the scratchy pot universe!

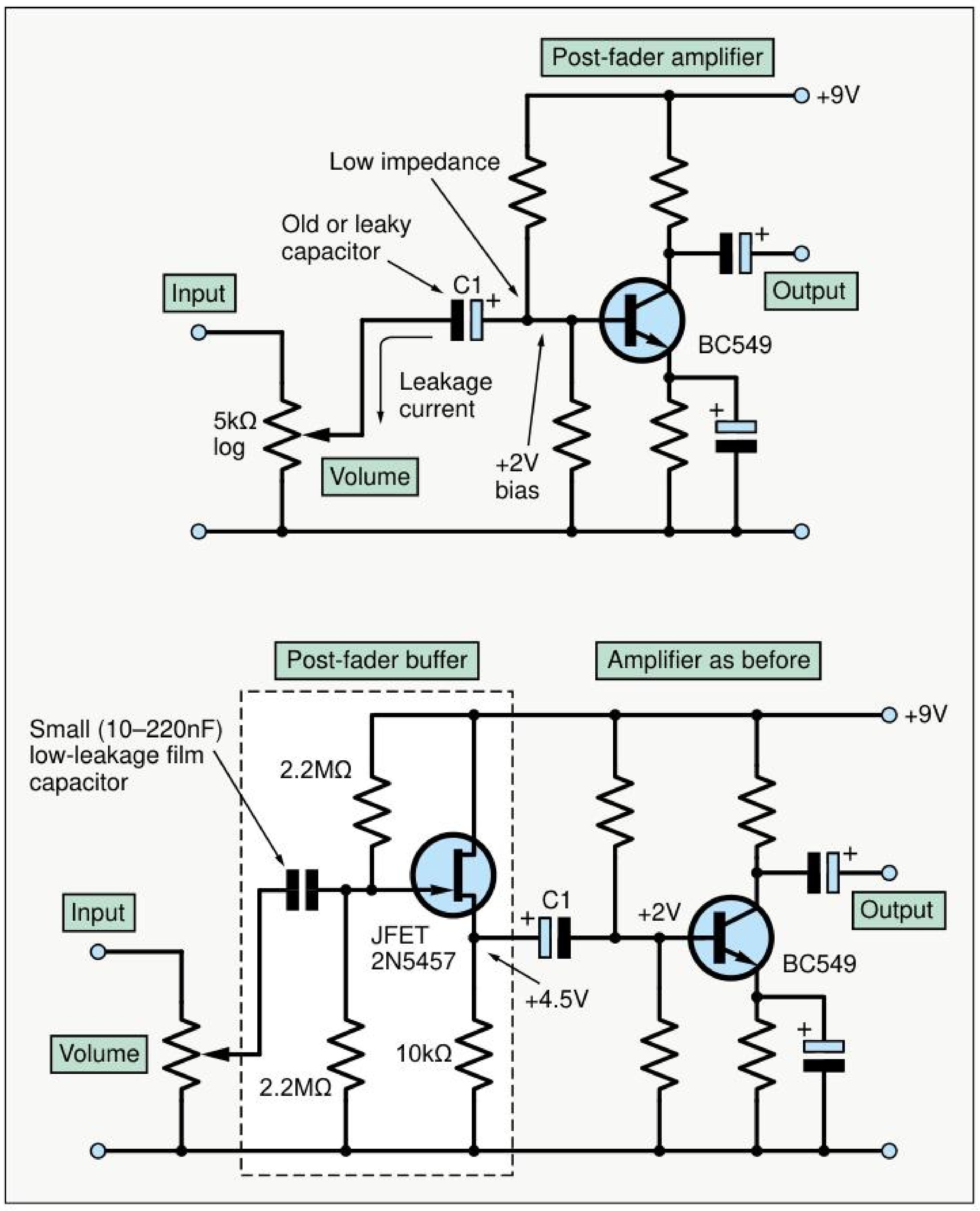

Fig.10. Avoid leaky electrolytic capacitors on a wiper by using post fader buffers (PFBs). Driving a volume control from a low impedance source makes the track resistance tolerance insignificant. Note reversal of interstage coupling capacitor (C1).

PE hands-on product review

EEVBlog

by Julian Edgar

121GW multimeter

An excellent tool available at a good price

I needed a new multimeter. I've used Fluke gear for years and have two high-quality Fluke multimeters. And then, for no apparent reason, one of the Fluke meters simply stopped turning on. But since I'd had that one for about a decade, I wasn't hugely put out. But then the other – a super-expensive, current model Fluke 287 – developed a fault where it says the leads are in the wrong sockets. (And when this fault is present – the fault is intermittent – you can't take a reading!) I browsed the web, and it turns out it's actually a common problem with Fluke meters. Considering how much I paid (about £750) and how long I'd had it (just a few years) I was very unimpressed. I was even less impressed when Fluke wanted £50 just to look at it – that was before any quote to repair it.

Non-Fluke meter

So, I started looking for a new, non-Fluke meter. And I looked and I looked. I wanted one with logging, min/max/average (the 'averaging' function is very important to me), a 50,000 count display and a fast-response bar graph. And of course, all this with at least decent accuracy.

And then I found a really unusual meter. It started as a crowdsourced design, but then ended up being made in South Korea by UEI Test Instruments. It is the work largely of Dave Jones, who runs EEVblog and who wanted a meter that had the features he desired. It has on-board logging to an internal micro-SD card, it has a low-burden mode when measuring current, it has in-built Bluetooth and talks to Android and Apple phones (and those phones can log and speak the measurements). You can even upgrade the firmware via the micro-SD card and perform a full digital calibration! It's also been around three or four years, so it's not a flash in the pan. And it costs just £160.

EEVBlog 121GW multimeter overview

Let's take a look at this meter from a strictly practical, hands-on perspective.

The meter is quite chunky: about 165 x 85 x 55mm (H x W x D) in its rubberised holster. That said, it easily fits in one hand and can be used with a probe clipped into one of the rear holders to allow one-hand probing, with the other hand free for the second probe. Talking of probes, they're of silicone construction – the whole meter feels good quality.

The display is large and easy to read, even in poor light, and the backlight is excellent – the best I have used in a multimeter. A smaller secondary display is activated in some functions (for example, it shows frequency when

Full disclosure

The reviewed meter was bought by the author for real work at the normal retail price.

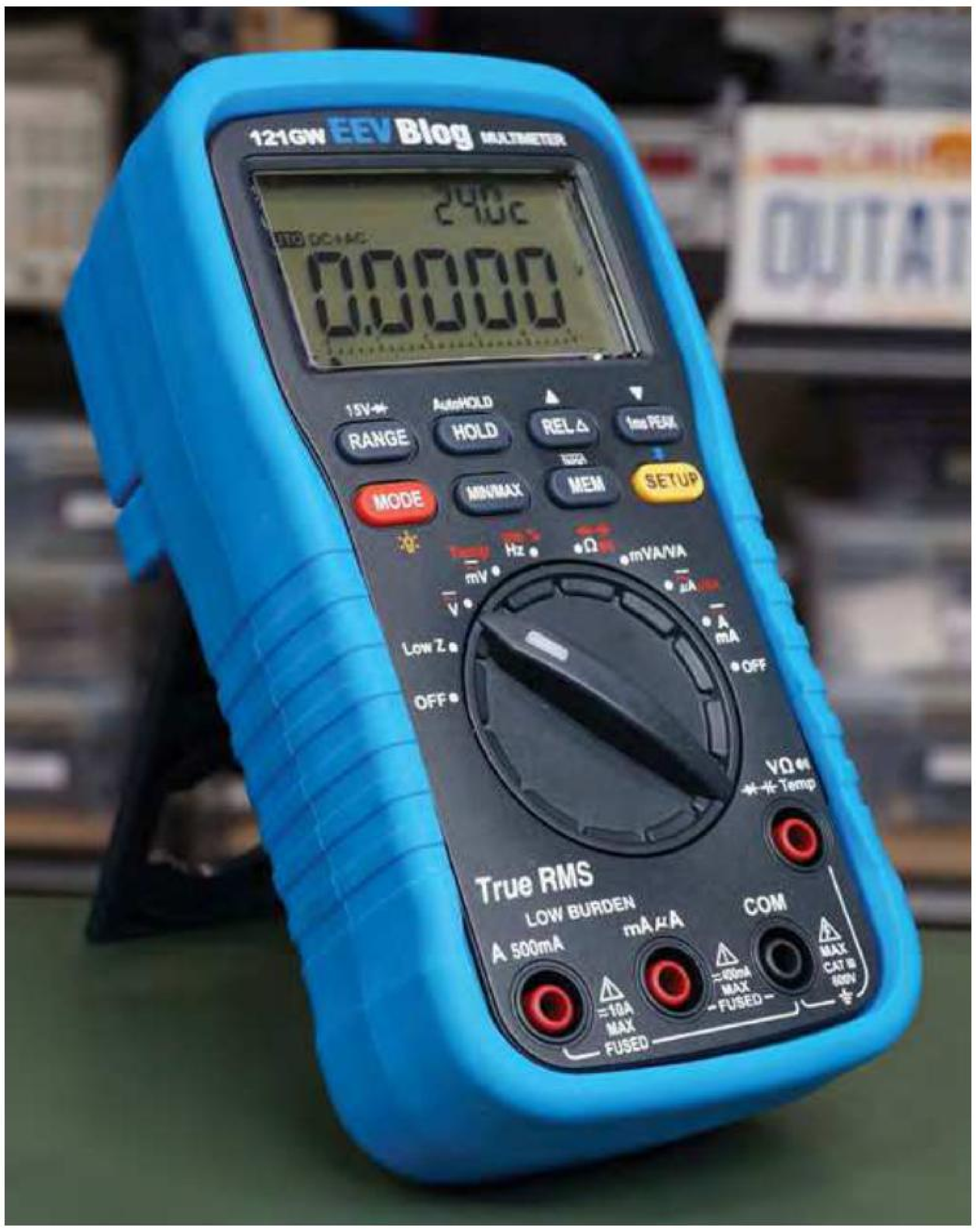

Fig.1. The EEVBlog 121GW is an unusually well-thought-out multimeter, with a range of functions including logging to an on-board micro-SD card, Bluetooth communication with a phone and in-field upgradeable firmware and calibration. It's also well priced!

measuring AC volts) and a fast response, horizontal bar graph is placed along the bottom of the display.

The meter uses four AA alkaline cells and one CR1220 button cell – the latter is for the real-time clock. Battery life is claimed to be 500 hours.

The meter is largely intuitive to use – anyone could pick it up and start making measurements without reading a word of the very clear 73-page downloadable manual. The rotating knob selects the usual range of measurements (V, mV, Hz, Ω…) and a secondary range is accessed by pressing the Mode button. Unfortunately, the secondary functions are shown on the meter in red, which is quite hard to read against the black plastic background. (The other functions are shown in white.)

One important feature to know about is that the meter remembers whatever sub-function you last selected. So, for example, if you have selected the continuity function under the Ω selection, the next time you turn on the meter and select Ω, continuity will be automatically selected. I find this very useful, as the meter becomes configured for your most-used functions.

A Low Z mode is available on the main selection dial. This low impedance mode, used on AC voltages, is designed to drain ghost voltages.

Other tricky measuring aspects included are that the current-measuring burden voltage (the voltage drop across the internal measuring resistor) can be displayed, continuity can be configured to sound the buzzer when the circuit is either closed or open, and diode measurement can be made with either a 3V or 15V supply. Finally, for some circuits, power (ie, simultaneous measurement of both current and voltage) can be directly displayed.

Handling data

The above features are all well and good (and no doubt for some people extremely useful) but for me the two standouts are the on-board logging and ability to communicate with a phone.

First, let’s look at logging. The data logging is activated by pressing the MEM button until a beep is heard and a counter starts on the secondary display. This counter shows the number of samples that have been taken, with logging able to be configured to occur at anything from 200ms to 999s (about 17min) intervals. The Auto Power Off function is disabled during logging. The logging is of whatever information is shown on the main and, if activated, the secondary displays.

Logging is halted via the same MEM button, and then you can review the latest logged data file by briefly pressing this button and using the ‘up/down’ arrow keys to scroll back through it. Unfortunately, pressing the MIN/MAX key doesn’t show these values from the logged data. You can also extract the micro-SD (but removing the meter’s back is required, using a Philip’s head screwdriver) and read the CSV file in Excel – for each logged point, this shows the time (to one second resolution), the selected meter function and the values. (Note: this logged data does show the maximum and minimum values.)

Bluetooth communication

The meter also has a Bluetooth function that allows it to communicate with your Android or Apple phone via a free, downloadable App. Having experienced some problematic multimeter communication approaches before, I was concerned that setting up the phone communication would be difficult – but in fact, it immediately worked.

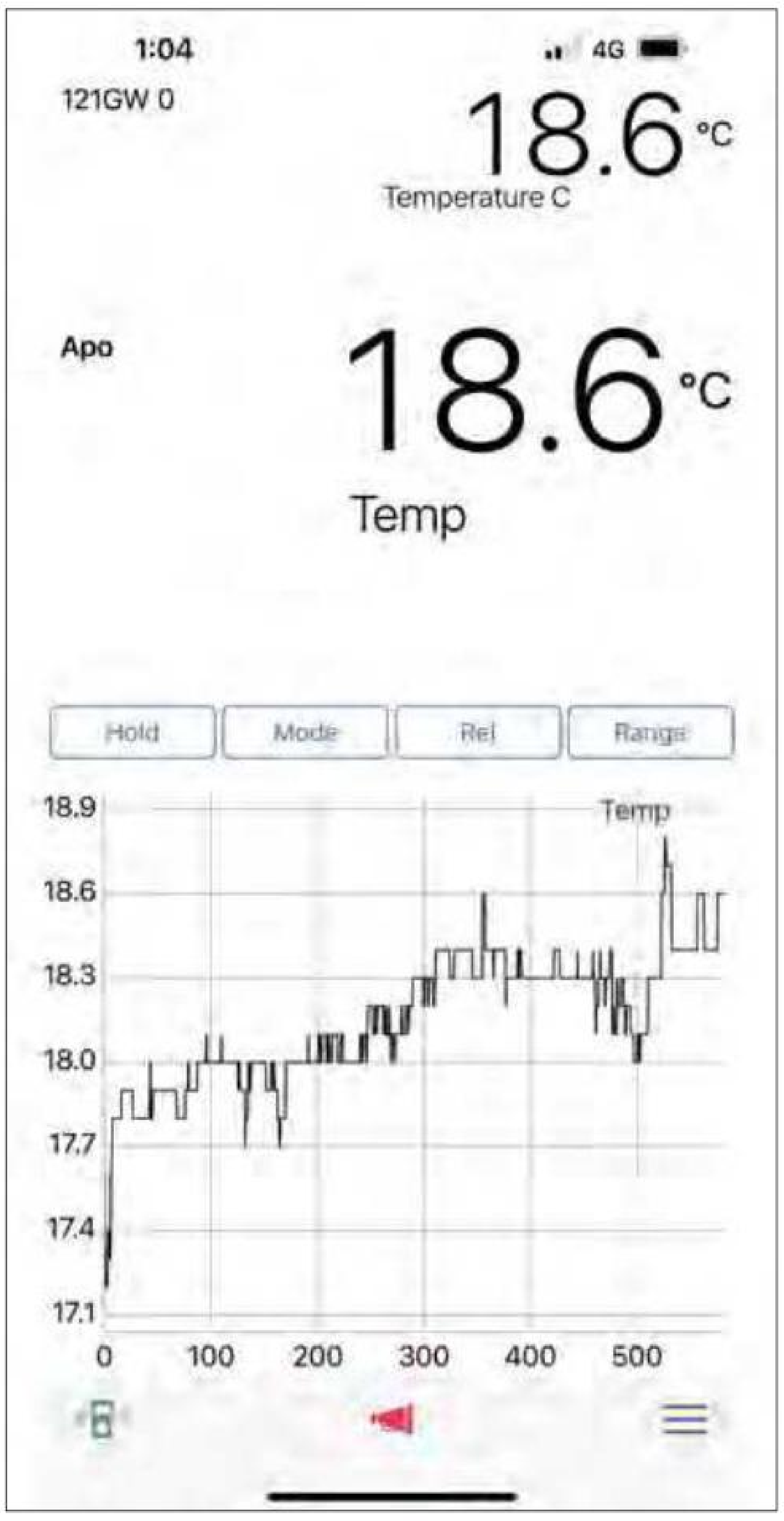

Fig.2. Screen grab from an iPhone connected to the multimeter via Bluetooth. In this case the phone was logging temperature at 200ms intervals and speaking the temperature every minute. The main display is using the supplied thermocouple to measure temperature, while the secondary display is showing temperature as sensed by the meter’s internal sensor.

From your phone you can select different multimeter functions (eg, Range, Relative and Hold), see a graph of live or logged data, and configure your phone to speak the current measurement – either periodically (from 3-60s intervals) or when a value changes. This is very cool feature indeed. For example, you can be monitoring a voltage (or temperature or frequency or…) and receive an oral indication only when the level changes. By using the Range button, you can even configure the sensitivity of the indication. Bluetooth range is about 10 metres, and the meter doesn’t automatically reconnect when back in range (you must do this manually).

I’ve not written about accuracy, because for most people’s applications, repeatability and linearity are more important than absolute accuracy. However, the meter typically has a claimed accuracy of better than ±1.5%+10 – the downloadable manual shows the accuracy specs for every range and function.

Finally, the meter has a bunch of set-up functions you typically never see. You can adjust the LCD contrast, check the meter’s internal battery voltage, give the meter a specific number ID (useful in companies having multiple meters) and turn the internal buzzer on and off.

I’m very pleased with the meter… and I am not going back to Fluke any time soon!

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PCBs for most recent *PE*/*EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

Double-sided | plated-through holes | solder mask

PROJECT	CODE	PRICE
AUGUST 2021		
Ol' Timer PCB	19104201	£11.95
Ol' Timer 8x8 RGB LED module using WS2812B	19104201-88	£8.95
Ol' Timer set of acrylic case pieces and spacer	19104201-ACR	£8.75
Ol' Timer DS3231 RTC IC wide SOIC-16	19104201-RTC	£5.95
Wideband Digital RF Power Meter	04106201	£9.75
Switchmode 78xx regulators ***(PACK of 5!)***	18105201	£7.95
Cool Beans SMAD display	CB-AUG21	£11.95
JULY 2021		
ATtiny816 Breakout / Dev Board with Capacitive Touch	24110181	£9.75
IR Remote Control Assistant (Jaycar version)	15005201	£8.95
IR Remote Control Assistant (Altronics version)	15005202	£8.95
PIC18F Development Board	PNM-JUL21	£12.95
Microphone Preamplifier	AO-JUL21	£11.95
JUNE 2021		
Roadies' Test Signal Generator (surface-mount version)	01005201	£8.95
Roadies' Test Signal Generator (through-hole version)	01005202	£9.95
Touchscreen Wide-range RCL Box (Resistor module)	04104201	£18.95
Touchscreen Wide-range RCL Box (Ind/Cap module)	04104202	
KickStart Part 3 – Gyrator-based Audio Filter	KS3-2021	£7.95
MAY 2021		
7-Band Equaliser (Mono)	01104201	£8.95
7-Band Equaliser (Stereo)	01104202	£10.95
Car Altimeter	05105201	£7.95
APRIL 2021		
Reflow Oven – DSP Active Crossover (CPU)	01106193	£19.95
Reflow Oven – DSP Active Crossover (Front panel)	01106195	
Reflow Oven – DSP Active Crossover (LCD)	01106196	
Frequency Reference Signal Distributor	CSE200103	£8.95
MARCH 2021		
Nutube Guitar Effects Pedal	01102201	£12.95
Programmable Thermal Regulator (Peltier Interface)	21109181	£18.95
Programmable Thermal Regulator (Peltier Driver)	21109182	
Tunable HF Preamp	CSE190502	£8.95
FEBRUARY 2021		
4G Remote Monitoring	27111191	£9.95
JANUARY 2021		
Nutube Valve Preamplifier	01112191	£12.95
Arduino DCC Controller	09207181	£10.95
DECEMBER 2020		
Pseudo-Random Sequence Generator	16106191	£7.95
Clever Charger	14107191	£11.95
PE Theremin Amplifier	AO-1220-01	£8.95
NOVEMBER 2020		
LED Christmas Tree (1 off)	16107181-1	£6.95
LED Christmas Tree (4 off)	16107181-2	£14.95
LED Christmas Tree (12 off)	16107181-3	£24.95
LED Christmas Tree (20 off)	16107181-4	£34.95
USB/SPI Interface Board	16107182	£5.95
45V/8A Power Supply PCB *plus* acrylic spacer	18111181	£14.95
45V/8A Power Supply front panel five-way display bezel	18111181-BZ	£3.95
Five-way LCD Panel Meter/Display	18111182	£7.95
OCTOBER 2020		
Digital Audio Millivoltmeter	04108191	£9.95
Precision Signal Amplifier	04107191	£7.95

PROJECT	CODE	PRICE
SEPTEMBER 2020		
PE Theremin PSU	AO-0920-01	£5.95
PE Theremin PSU transformer	AO-0920-02	£7.95
Micromite Explore-28	07108191	£6.95
Ultrabrite LED Driver	16109191	£6.95
AUGUST 2020		
Micromite LCD BackPack V3	07106191	£9.95
Steering Wheel Audio Button to Infrared Adaptor	05105191	£7.95
JULY 2020		
AM/FM/CW Scanning HF/VHF RF Signal Generator	04106191	£13.95
Speech Synthesiser with the Raspberry Pi Zero	01106191	£5.95
PE Mini-organ PCB	AO-0720-01	£14.95
PE Mini-organ selected parts	AO-0720-02	£8.95
High-current Solid-state 12V Battery Isolator – control	05106191	£6.95
High-current Solid-state 12V Battery Isolator FET (2oz)	05106192	£9.95
JUNE 2020		
Arduino breakout board – 3.5-inch LCD Display	24111181	£6.95
Six-input Audio Selector main board	01110191	£10.95
Six-input Audio Selector switch panel board	01110192	

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Ultra-low-distortion Preamplifier Input Selector	01111112	£11.25
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Universal Regulator	18103111	£7.95
433MHz Wireless Data Repeater	15004191	£8.50
Bridge-mode Adaptor for Amplifier	01105191	£7.95
iCEstick VGA Terminal	02103191	£5.95
Analogue noise with tilt control	AO-0520-01	£7.95
Audio Spectrum Analyser	PM-0520-01	£8.95
APRIL 2020		
Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
Diode Curve Plotter	04112181	£10.95
Steam Train Whistle / Diesel Horn Sound Generator	09106181	£8.50
Universal Passive Crossover (one off)	UPC0320	£12.50
FEBRUARY 2020		
Motion-Sensing 12V Power Switch	05102191	£5.95
USB Keyboard / Mouse Adaptor	24311181	£8.50
DSP Active Crossover (ADC)	01106191	£29.95
DSP Active Crossover (DAC) ×2	01106192	
DSP Active Crossover (CPU)	01106193	
DSP Active Crossover (Power/routing)	01106194	
DSP Active Crossover (Front panel)	01106195	
DSP Active Crossover (LCD)	01106196	
JANUARY 2020		
Isolated Serial Link	24107181	£8.50
DECEMBER 2019		
Extremely Sensitive Magnetometer	04101011	£16.75
Four-channel High-current DC Fan and Pump Controller	05108181	£8.75
Useless Box	08111181	£11.50
NOVEMBER 2019		
Tinnitus & Insomnia Killer (Jaycar case – see text)	01110181	£9.95
Tinnitus & Insomnia Killer (Altronics case – see text)	01110182	£9.95
OCTOBER 2019		
Programmable GPS-synced Frequency Reference	04107181	£11.50
Digital Command Control Programmer for Decoders	09107181	£9.95
Opto-isolated Mains Relay (main board)	10107181	£11.50
Opto-isolated Mains Relay (2 × terminal extension board)	10107182	
AUGUST 2019		
Brainwave Monitor	25108181	£12.90
Super Digital Sound Effects Module	01107181	£6.95
Watchdog Alarm	03107181	£8.00
PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
PE Theremin component pack (see p.56, August 2019)	PETY0819	£15.00
JULY 2019		
Full-wave 10A Universal Motor Speed Controller	10102181	£12.90
Recurring Event Reminder	19107181	£8.00
Temperature Switch Mk2	05105181	£10.45
JUNE 2019		
Arduino-based LC Meter	04106181	£8.00
USB Flexitimer	19106181	£10.45

PROJECT	CODE	PRICE
MAY 2019		
2× 12V Battery Balancer	14106181	£5.95
Deluxe Frequency Switch	05104181	£10.45
USB Port Protector	07105181	£5.95
APRIL 2019		
Heater Controller	10104181	£14.00
MARCH 2019		
10-LED Bargraph Main Board	04101181	£11.25
+Processing Board	04101182	£8.60
FEBRUARY 2019		
1.5kW Induction Motor Speed Controller	10105122	£24.95
NOVEMBER 2018		
Super-7 AM Radio Receiver	06111171	£15.95
OCTOBER 2018		
6GHz+ Touchscreen Frequency Counter	04110171	£12.95
Two 230VAC MainsTimers	10108161	£11.95
	10108162	
SEPTEMBER 2018		
3-Way Active Crossover	01108171	£17.95
Ultra-low-voltage Mini LED Flasher	16110161	£5.95
AUGUST 2018		
Universal Temperature Alarm	03105161	£7.95
Power Supply For Battery-Operated Valve Radios	18108171	£24.95
	18108172	
	18108173	
	18108174	
JULY 2018		
Touchscreen Appliance Energy Meter – Part 1	04116061	£14.95
Automotive Sensor Modifier	05111161	£12.95
JUNE 2018		
High Performance 10-Octave Stereo Graphic Equaliser	01105171	£14.95
MAY 2018		
High Performance RF Prescaler	04112162	£10.45
Micromite BackPack V2	07104171	£8.45
Microbridge	24104171	£5.95
APRIL 2018		
Spring Reverberation Unit	01104171	£13.95
DDS Sig Gen Lid	Black	£5.95
DDS Sig Gen Lid	Blue	£5.95
DDS Sig Gen Lid	Clear	£5.95
MARCH 2018		
Stationmaster Main Board	09103171	£17.75
+ Controller Board	09103172	
SC200 Amplifier Module – Power Supply	01109111	£16.45
FEBRUARY 2018		
GPS-Synchronised Analogue Clock Driver	04202171	£11.95
High-Power DC Motor Speed Controller – Part 2		
+ Control Board	11112161	£11.95
+ Power Board	11112162	£15.30
JANUARY 2018		
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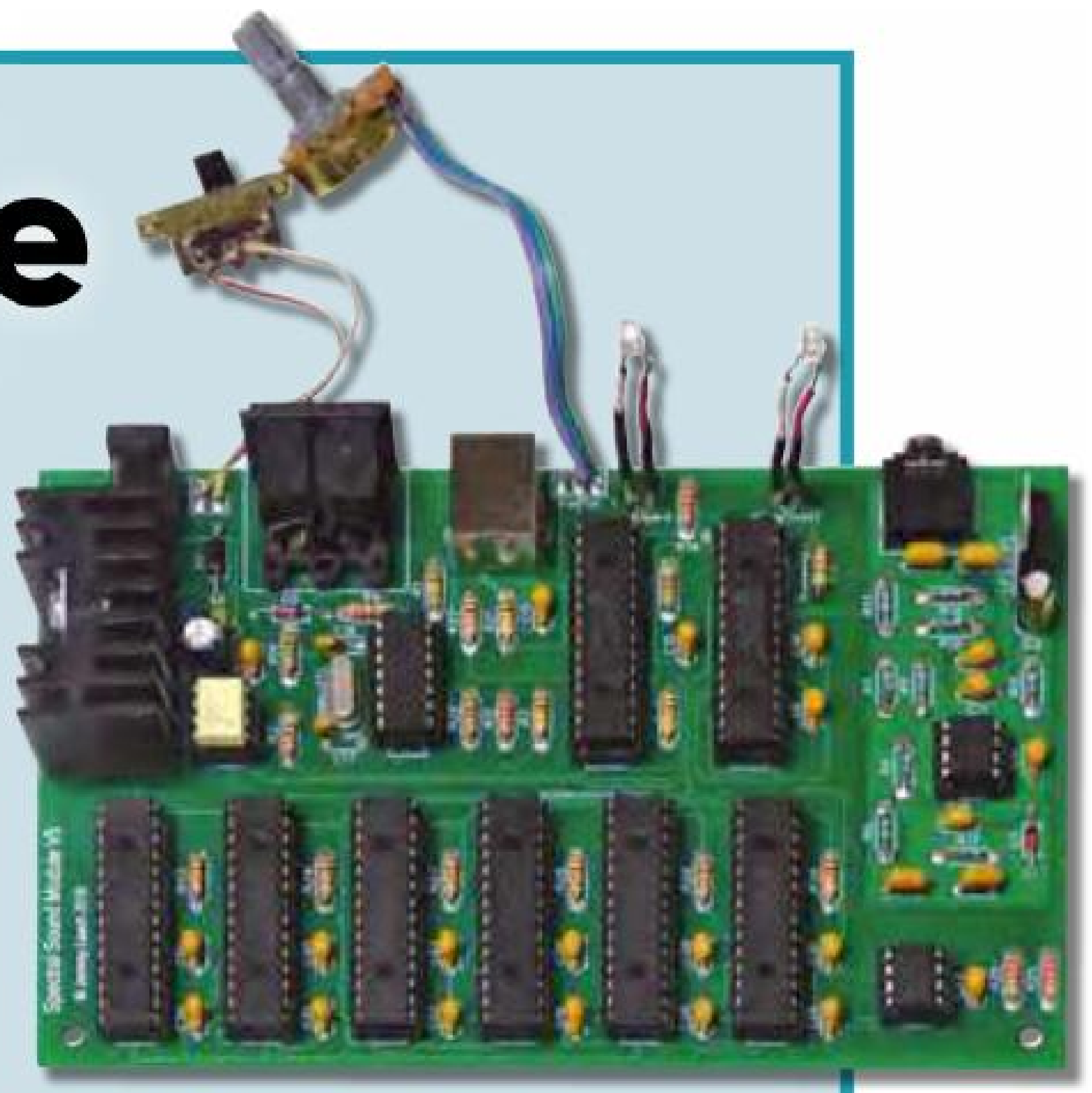
Next Month – in the July issue



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MOS Air Quality Sensors

Not everything you breath is oxygen and nitrogen, and if you are worried about what's in the air then you need a sensor to analyse your local atmosphere. Next month, we'll have a detailed investigation of some of the currently available MOS (metal-oxide semiconductor) air quality sensor modules. Plus, we'll include tips on how to hook them up to an Arduino. These inexpensive devices can detect ammonia, nitrous oxides, carbon dioxide, carbon monoxide alcohol, benzene, hydrogen, methane and smoke.

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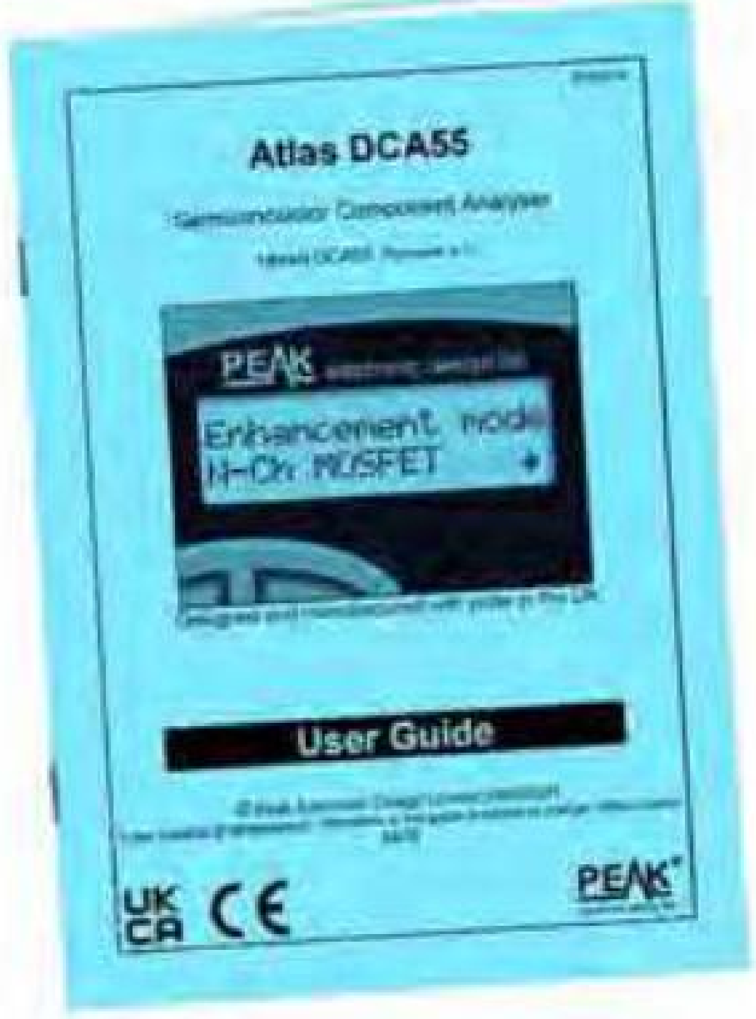
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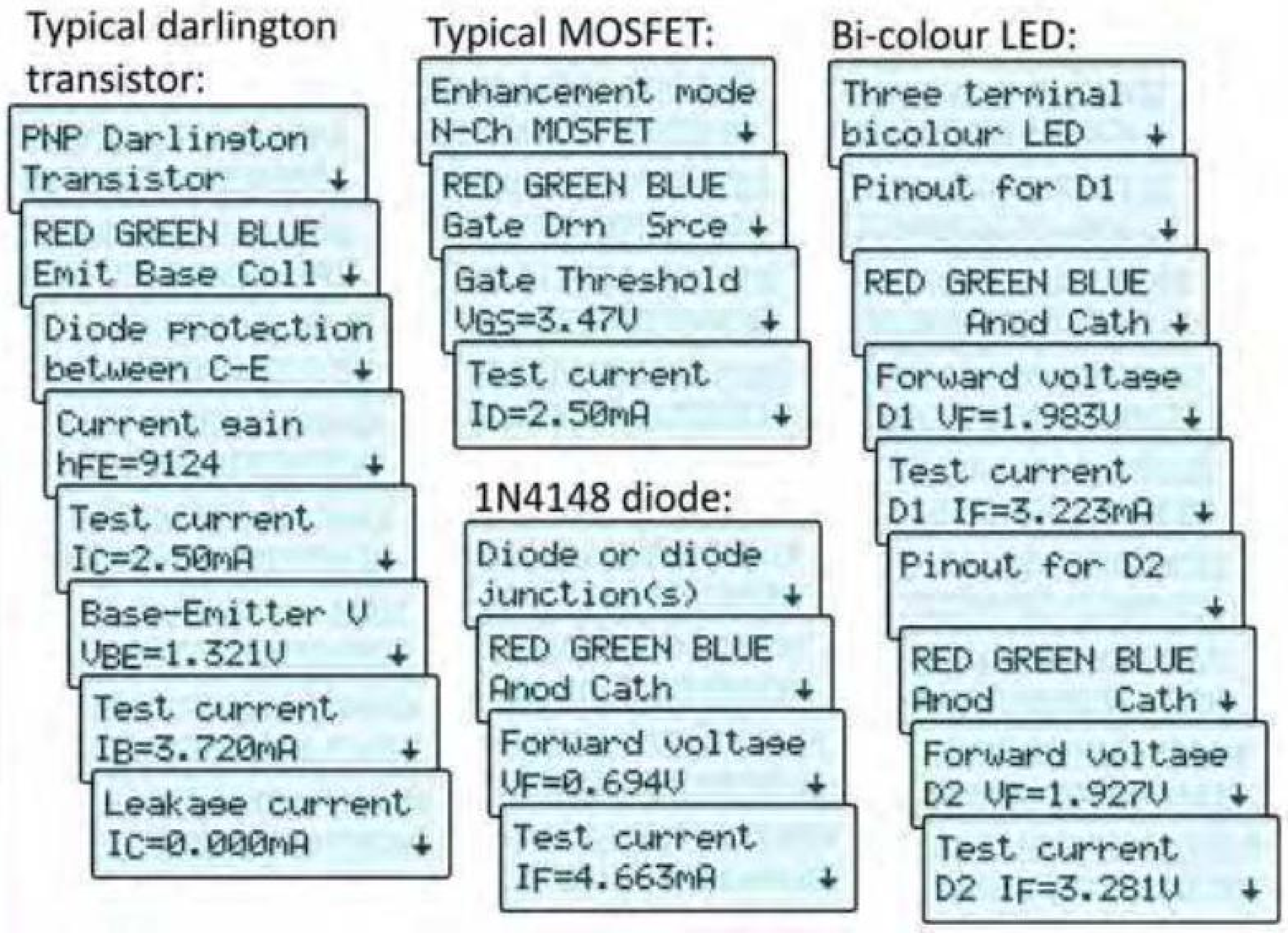

Typical darlington transistor:

```
PNP Darlington
Transistor    ↓
RED GREEN BLUE
Emit Base Coll ↓
Diode protection
between C-E   ↓
Current gain
hFE=9124      ↓
Test current
IC=2.50mA     ↓
Base-Emitter V
VBE=1.321V    ↓
Test current
IB=3.720mA    ↓
Leakage current
IC=0.000mA    ↓
```

Typical MOSFET:

```
Enhancement mode
N-Ch MOSFET   ↓
RED GREEN BLUE
Gate Drn  Srce ↓
Gate Threshold
VGS=3.47V     ↓
Test current
ID=2.50mA     ↓
```

1N4148 diode:

```
Diode or diode
junction(s)   ↓
RED GREEN BLUE
Anod Cath     ↓
Forward voltage
VF=0.694V     ↓
Test current
IF=4.663mA    ↓
```

Bi-colour LED:

```
Three terminal
bicolour LED  ↓
Pinout for D1
              ↓
RED GREEN BLUE
     Anod Cath ↓
Forward voltage
D1 VF=1.983V  ↓
Test current
D1 IF=3.223mA ↓
Pinout for D2
              ↓
RED GREEN BLUE
Anod      Cath ↓
Forward voltage
D2 VF=1.927V  ↓
Test current
D2 IF=3.281V  ↓
```

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